Integrated Micro-scale Power Conversion

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Sarah Bedair, PhD

Sensors & Electron Devices Directorate
U.S. Army Research Laboratory
Adelphi, MD 20783
sarah.s.bedair.civ@mail.mil

Collaborators:

ARL:
- Brian Morgan, Ph.D.
- Christopher Meyer, Ph.D.
- Iain Kierzewski
- Jeffrey Pulskamp
- Ronald Polcawich, Ph.D.

U. Florida:
- Xue Lin
- Chris Dougherty
- Prof. David Arnold
- Prof. Rizwan Bashirullah

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE
Integrated Micro-scale Power Conversion

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory,Sensors & Electron Devices Directorate,2800 Powder Mill Road,Adelphi,MD,20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees'/Contractors' Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL.

14. ABSTRACT

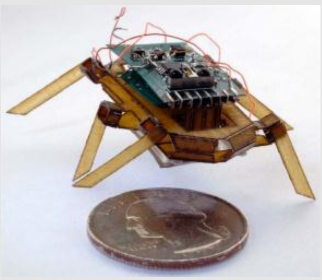
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**38**	

Autonomous System Technologies

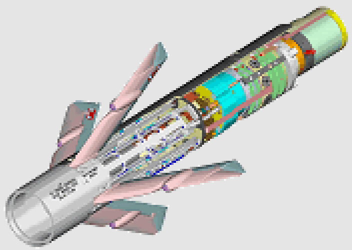
ARMY Platform Needs

MAST



Scale
- Miniature
- Multi-input / output
- Range of input voltages
- Output voltage, 1 V – 100's V
- < 1W

Missile health monitoring units



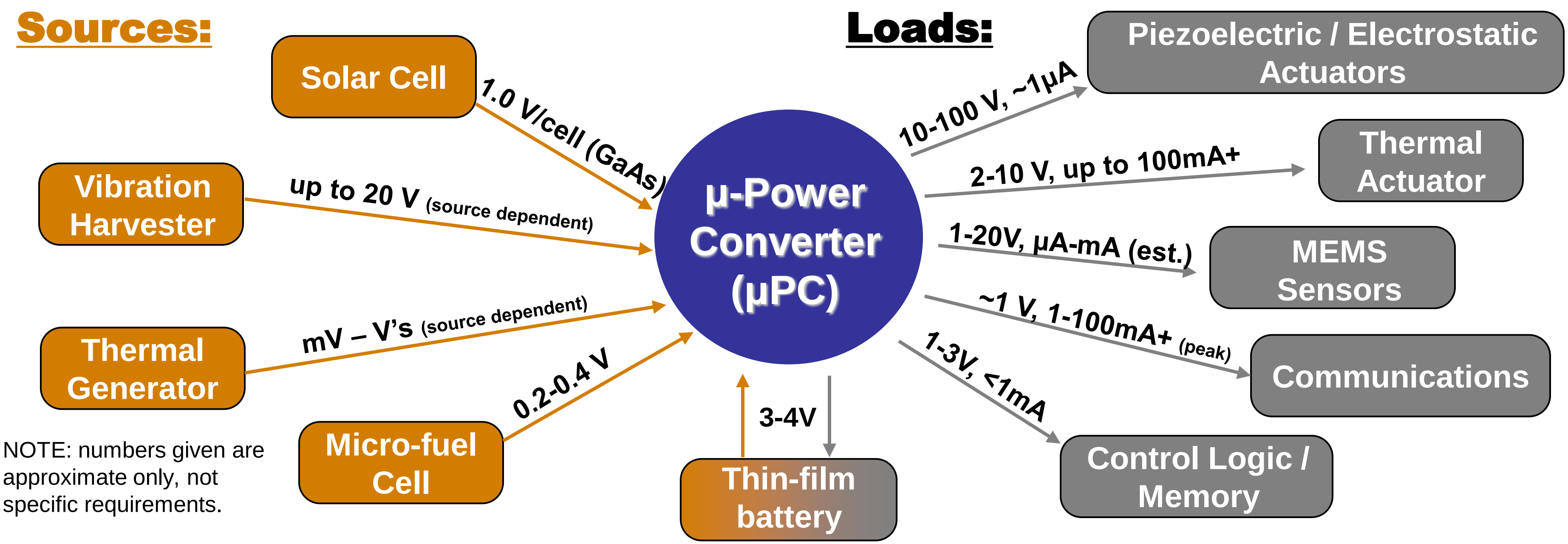
Lifetime
- Micro-watt saving adds weeks to battery life
- High efficiency w/ light loads
- μW's continuous
- 10s of mW bursts
- 15-20 yrs operating lifetime

ARL Blue radio

Lifetime & scale & speed
- "Power converters…one of biggest challenges"
- Moderate efficiency (>70%) w/ light loads
- Response time < 100usec
- Lots of outputs – e.g. 11.4V (5mA), 3.3 (50mA)

Many other applications or spin offs (missile prime power, soldier power managers, RF devices, TTL, etc)

Micro Power Converters (μPC)



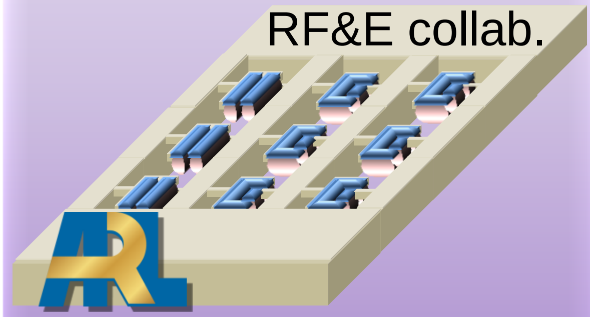
NOTE: numbers given are approximate only, not specific requirements.

ARL / U. Florida Approach

- **Leverage CMOS to increase frequency and reduce passive size**
- **Hybrid integration with MEMS passives, particularly inductors**

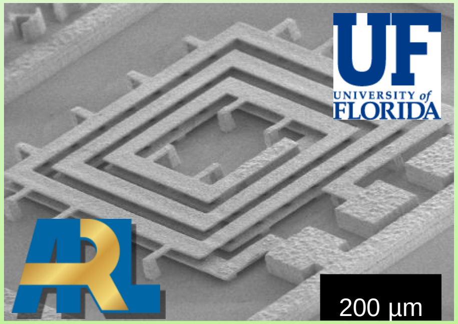
Integrated converters

<u>Piezo-transformers & capacitors</u>



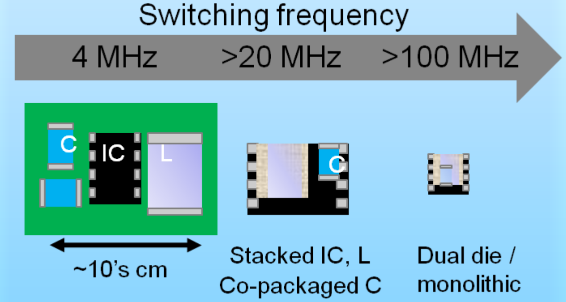
<u>Magnetics</u>

- ARL / UF Cu inductors

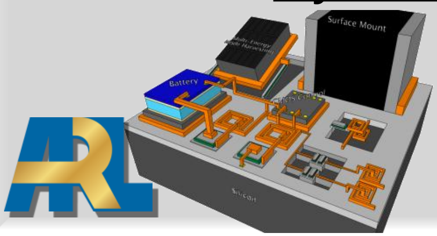


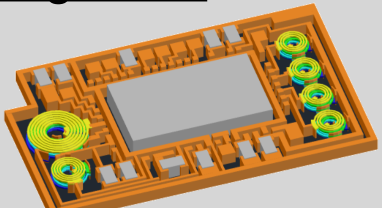
<u>CMOS / control</u>

Prof. Rizwan Bashirullah

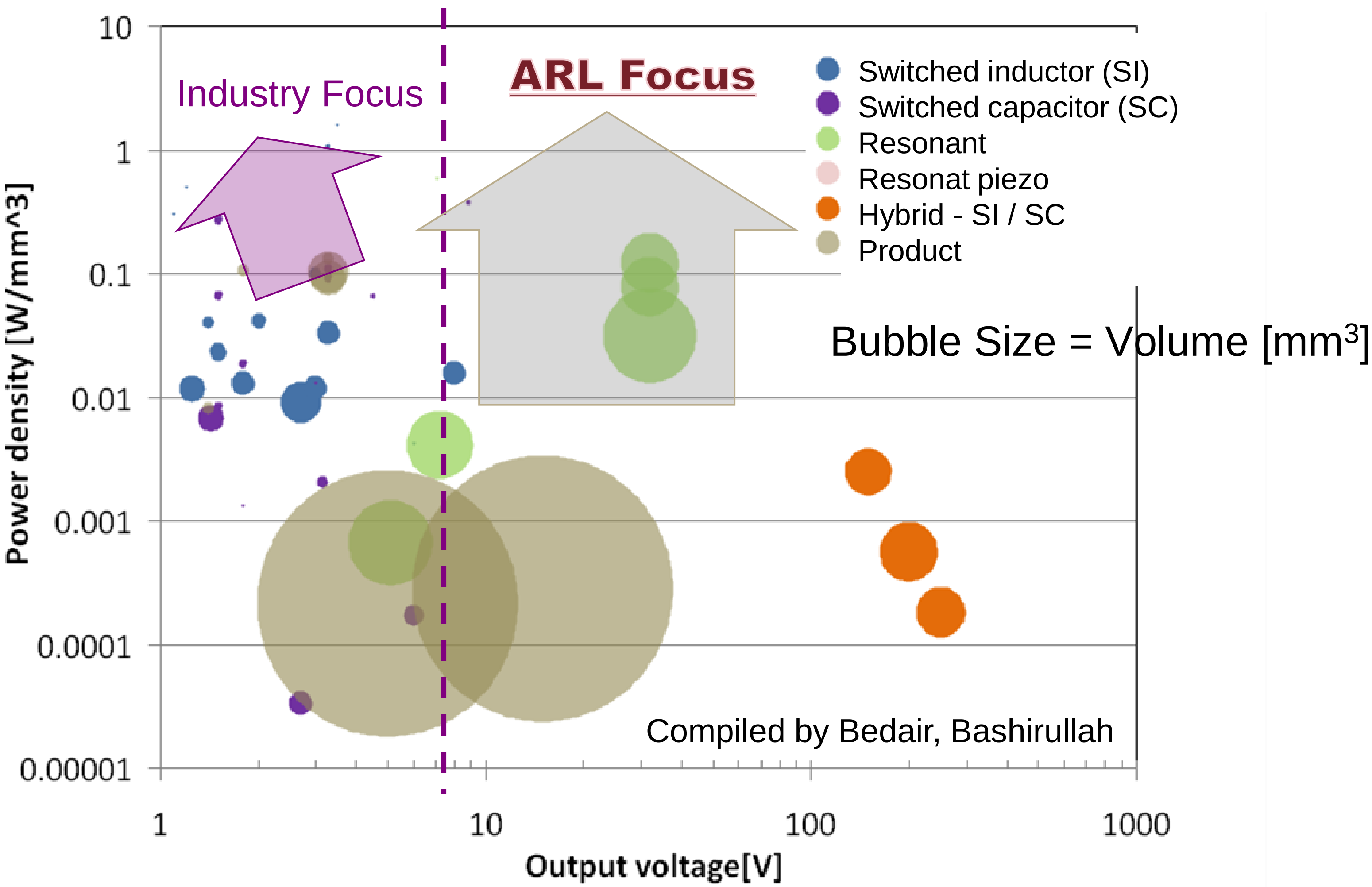


<u>Hybrid integration</u>



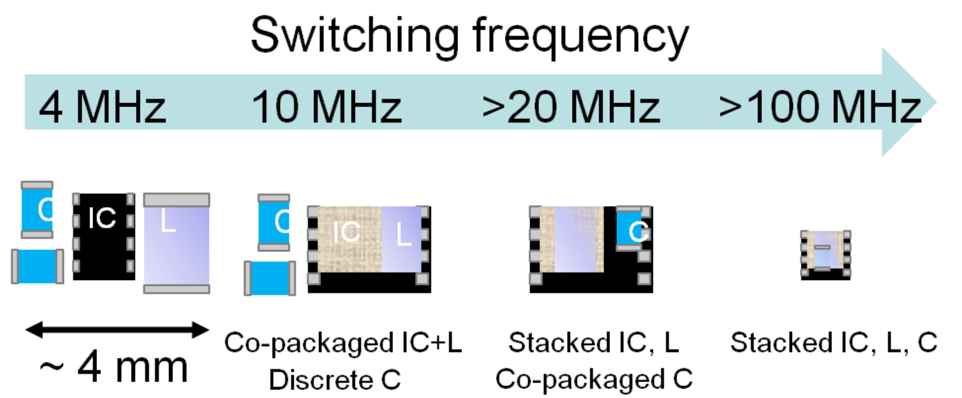


Power converters survey

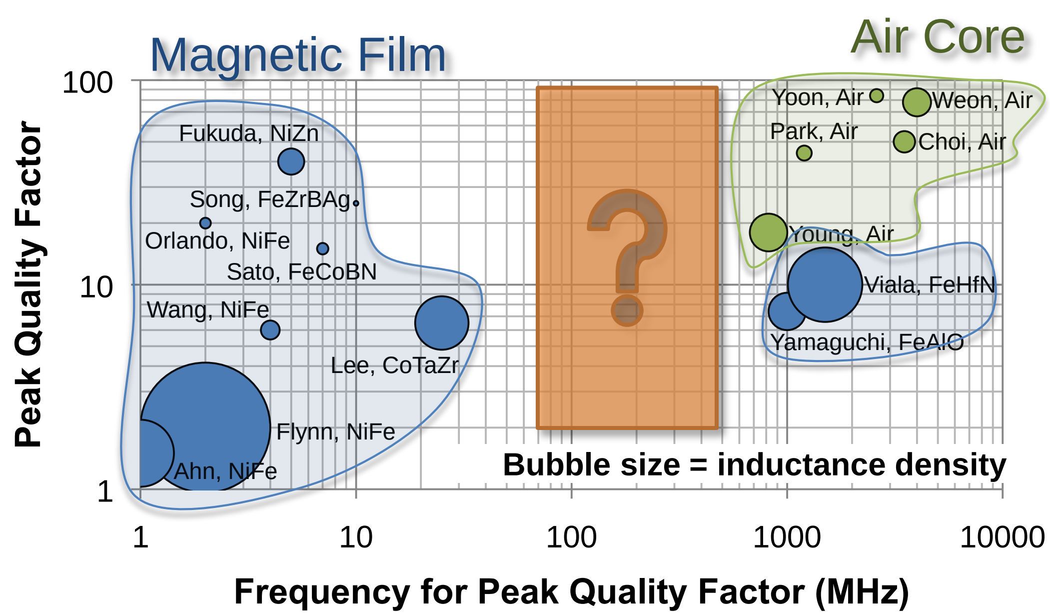


High Frequency Switching

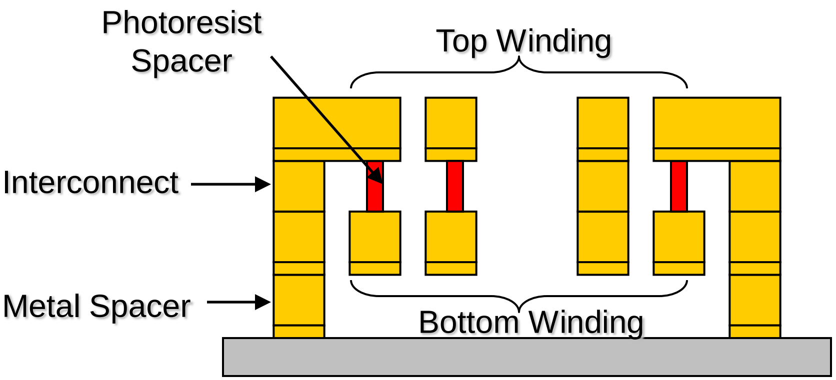
- **Increase switching frequency:**
  - Equivalent reactance with lower-valued passives.
- **Magnetic losses increase:**
  - Copper losses,
    - Skin and proximity effects;
  - Magnetic film losses;
    - Hysteresis,
    - Eddy currents,
    - Domain dynamics.
- **Increase magnetic switching frequency?**
  - Needs high bulk resistivity.
  - Needs fast moment reversal.
  - Needs to be compatible.
- **Air core?**
  - Needs higher inductance densities.
  - Needs greater quality factor at lower frequencies.



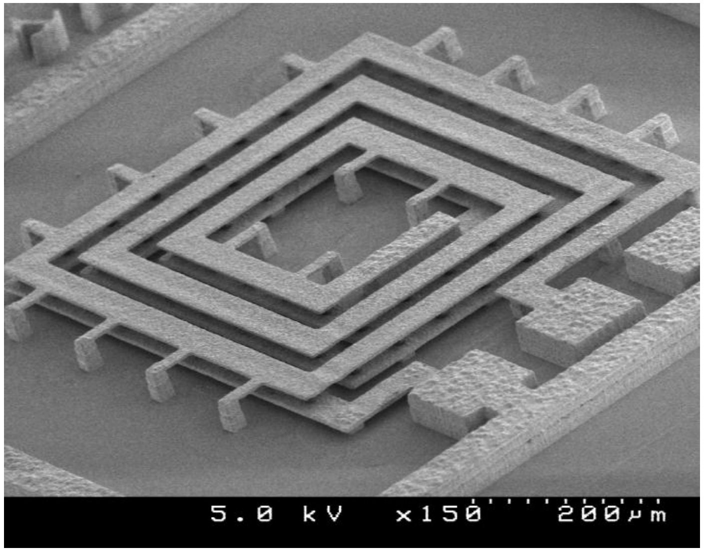
**Adapted from Tyndall Institute*



Inductor Fabrication

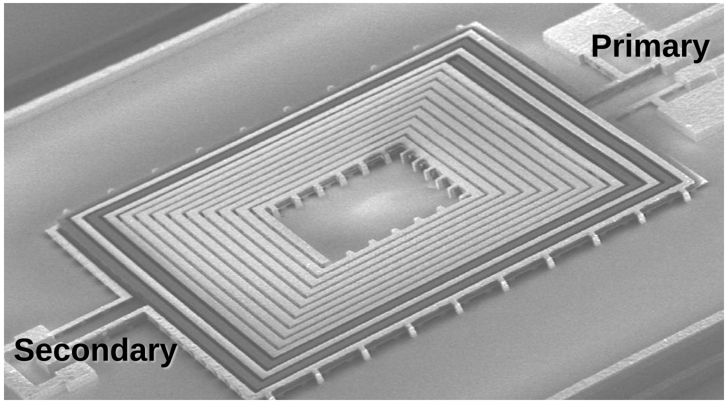


Inductor Cross Section



Air core MEMS Inductor

- **Process: electroplate copper through selectively exposed photoresist molds**
  - Four independent copper layers, 10-30µm per layer.
  - Ability to create polymer parts from remnant photoresist.
- **Vertical spacing off substrate to reduce coupling/interference**
- **Identical process flow for inductors or transformers**

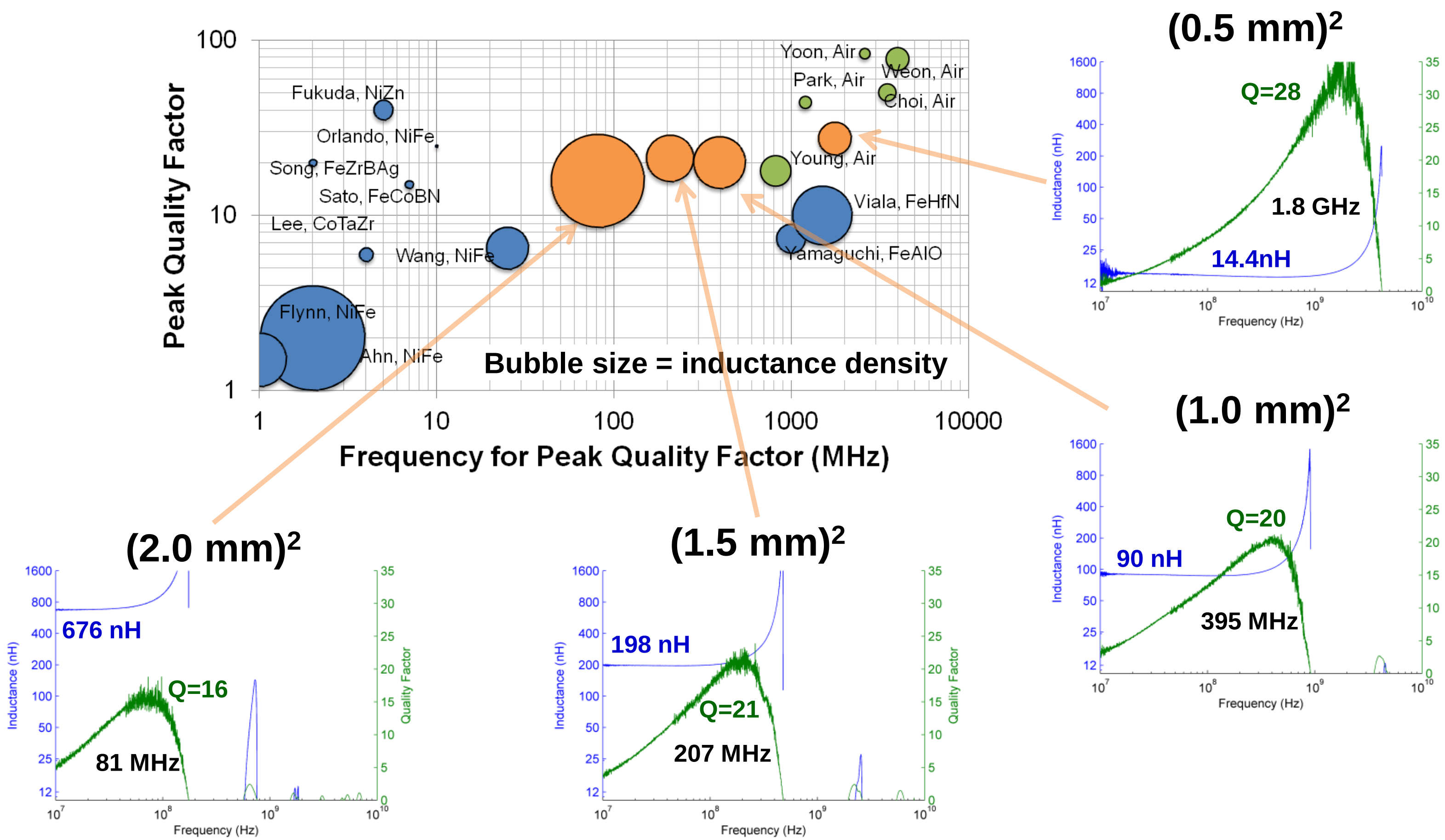


Air core MEMS Transformer

**Meyer et al, Hilton Head 2010*

Small Signal Characterization

- Various size inductors on Pyrex.
- RF characterization with VNA.
- Peak Q's > 20, inductance densities >100 nH/mm^2.

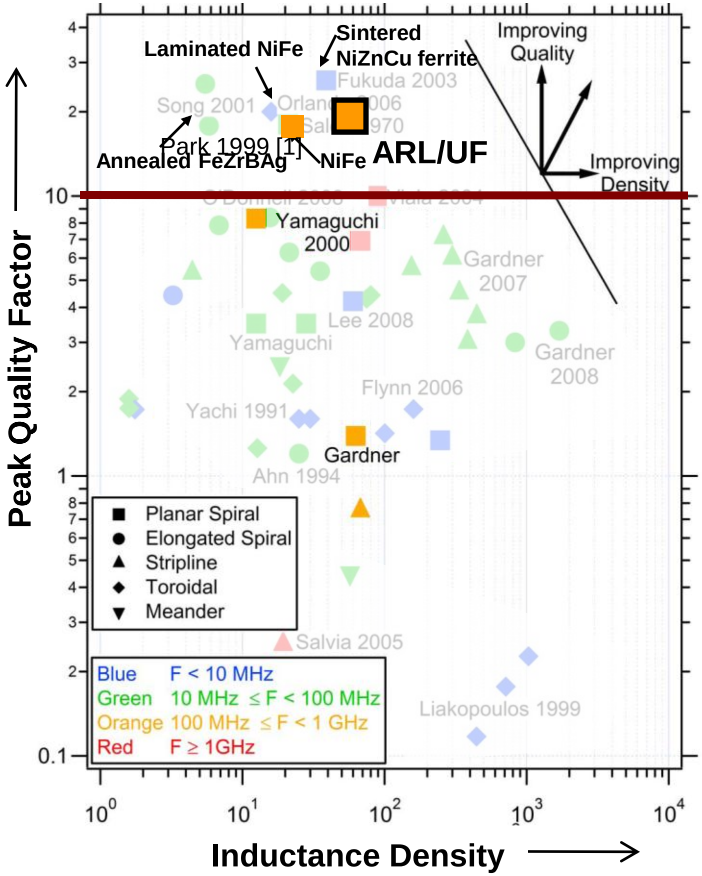


*Meyer et al., IEEE Trans on Magnetics 2010
*Meyer et al., ECS 2011

How do we compare?

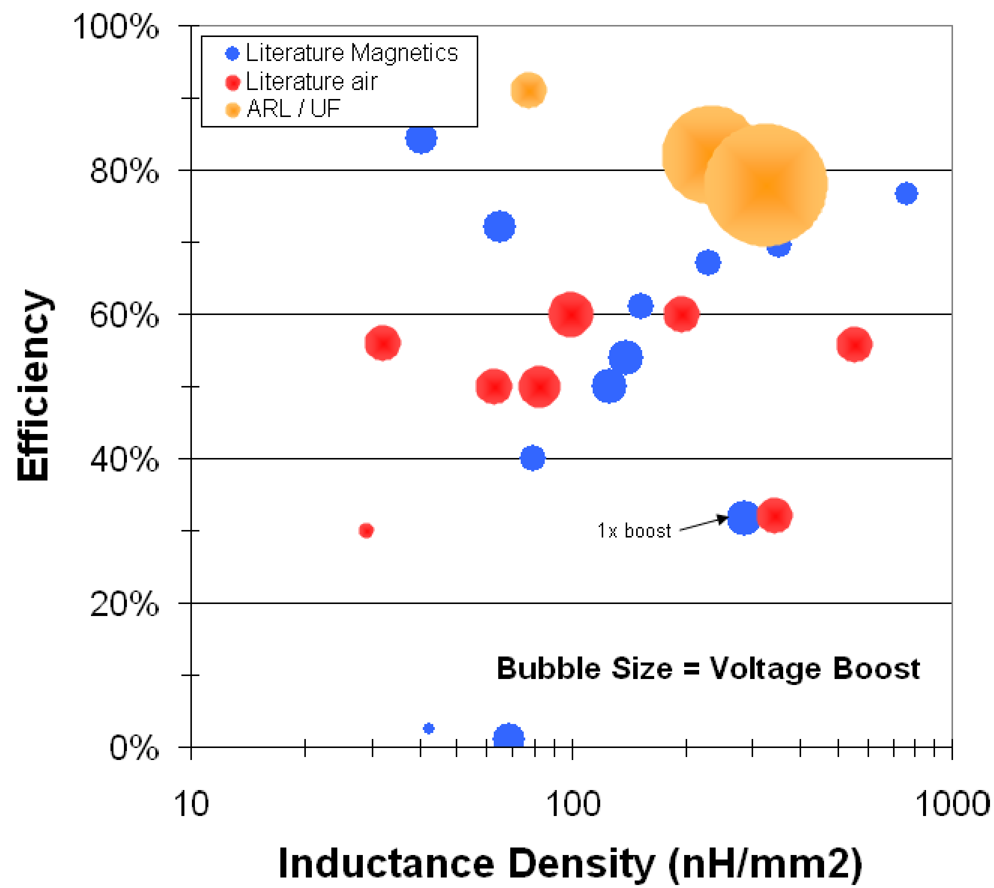
Micro-Inductors

(mostly magnetic film)



Gardner, et al., "Review of On-Chip Inductor Structures with Magnetic Films," *IEEE TMAG*, 2009.

Micro-Transformers

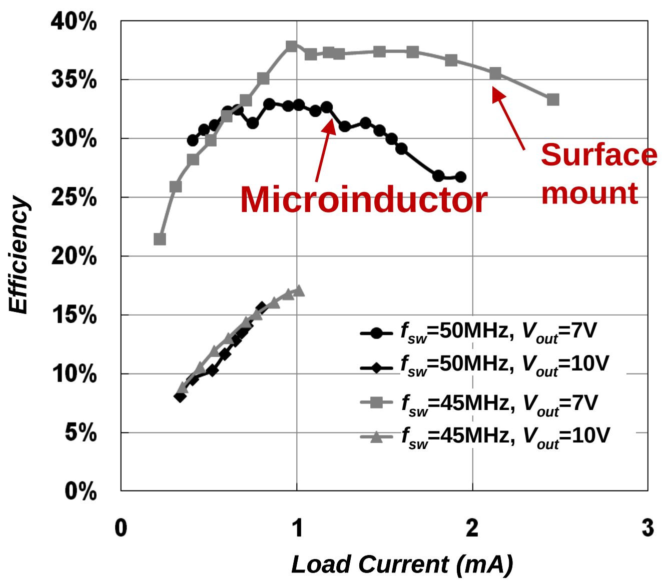


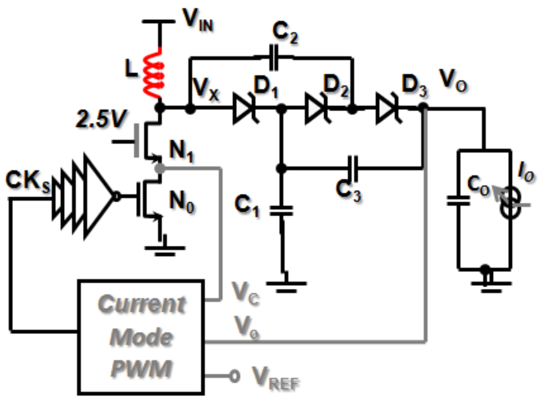
→ Significantly less transformer work in literature

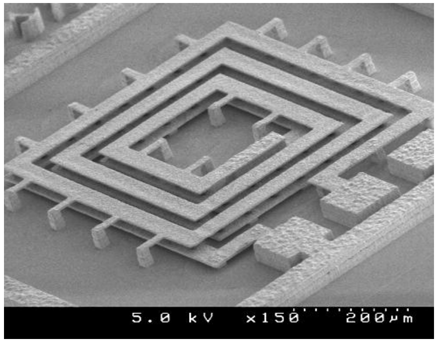
[1] J. Y. Park and M. G. Allen, "High Q Spiral-Type Microinductors on Silicon Substrates," *IEEE TMAG*, 1999.

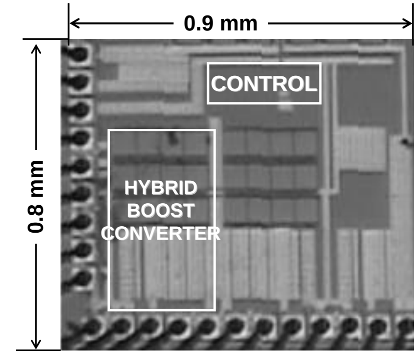
Testing with HF Converter

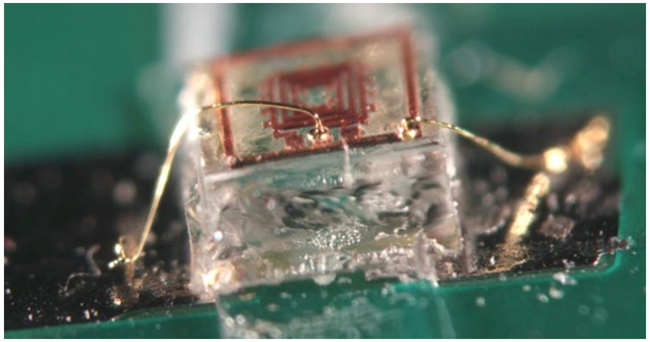
- **0.27 mm² inductor w/in hybrid boost converter.**
  - SI boost followed by 2 SC stages.
  - 130 nm, 1.2 V CMOS, f_{sw} = **100 MHz**.
  - V_{out} = 7 V from 1.2 V input (**6x conversion**).
- **Inductor wirebonded to PCB.**
- **Performance limited at higher current levels by winding resistance.**









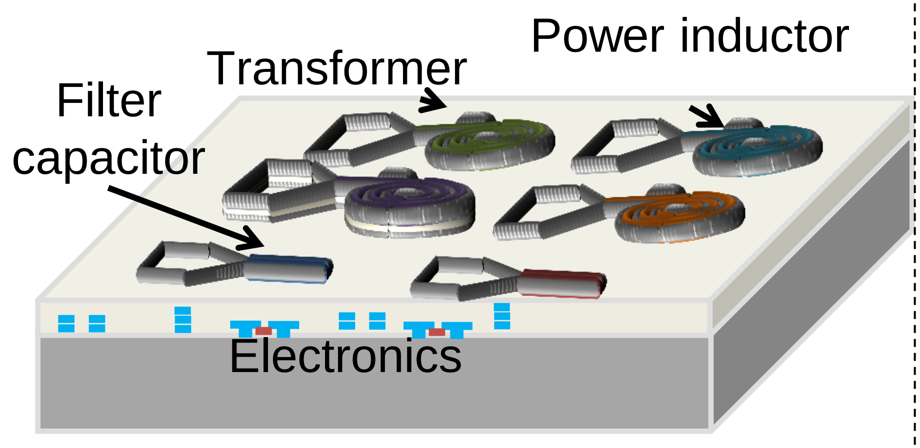


*Xue et al., APEC 2011

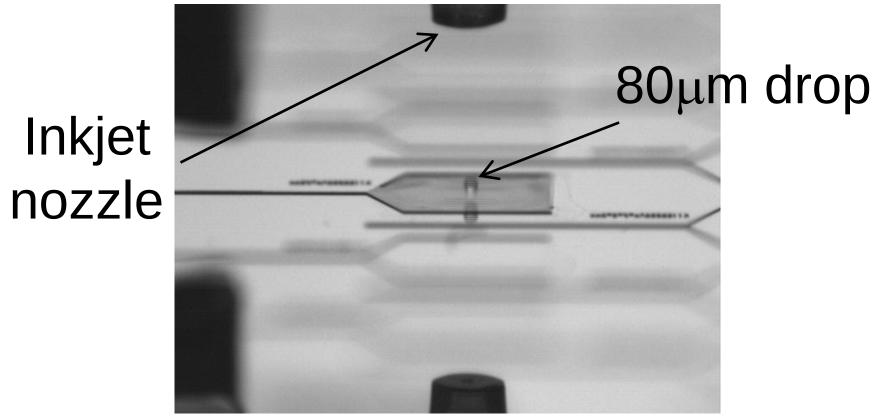
Nanoparticle Dosing for Passives

- **Challenge**
  - Single chip integration of CMOS with dielectrics & magnetic materials
  - Temperature / fabrication incompatibility
- **Approach**
  - Well and capillary delivery system
  - Dissolve or suspend nanoparticles
  - Dose structures with appropriate nanoparticles:
    - High-k dielectrics for capacitors
    - Magnetics for inductors
- **Advantages**
  - Room temperature
  - Material flexibility
  - Complex 3-D geometries

Motivation: monolithic



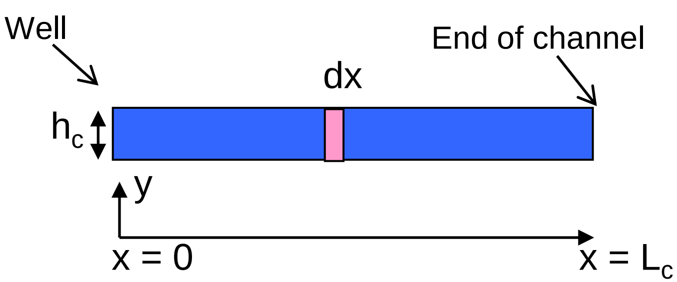
Deposit using inkjet printing



Theory: nanoparticle transfer in micro-capillary

- **Evaporated solvent in channel is replenished by the well**

Channel cross section

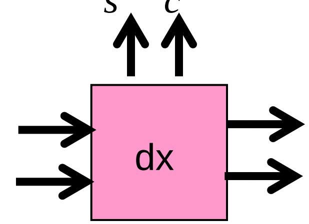


Mass loss due to evaporation (kg/sec)

$$J_s w_c dx$$

Solvent into dx (kg/sec)

$$\rho w_c h_c v(x,t)$$



Solvent out of dx (kg/sec)

$$\rho w_c h_c v(x+dx,t)$$

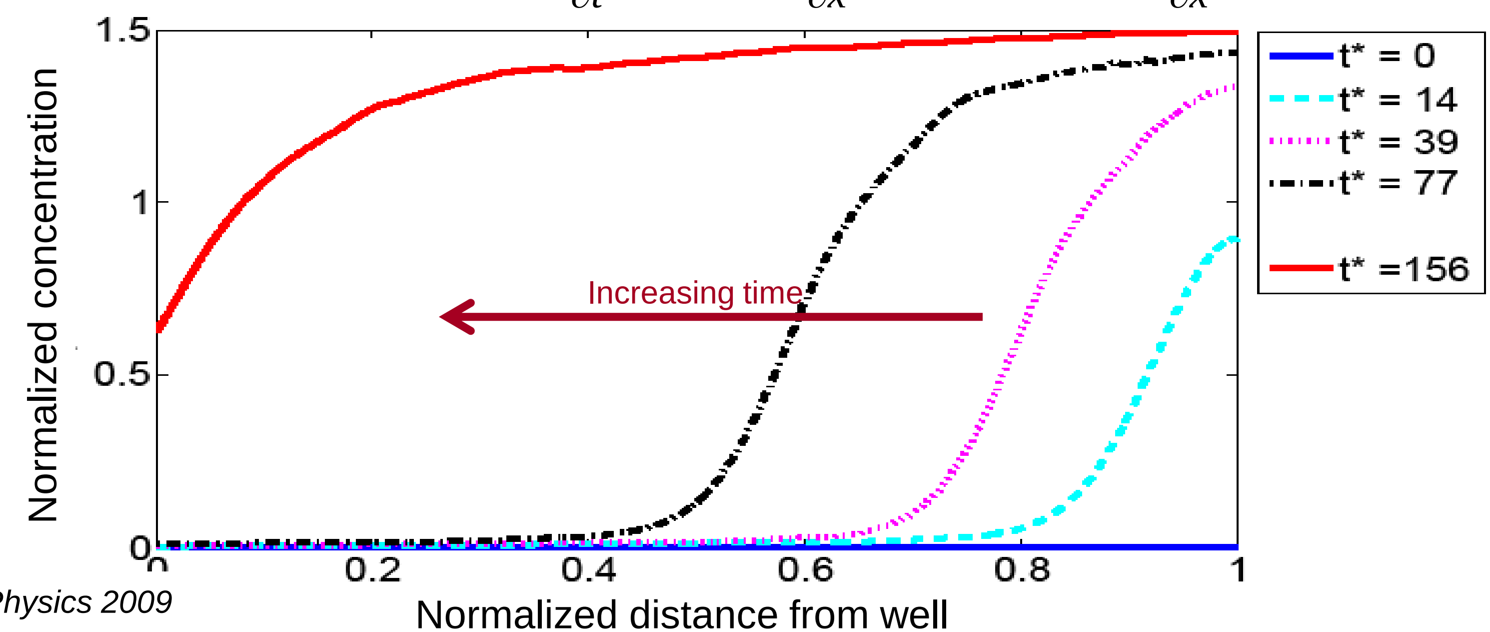
Total solvent mass rate of change

$$\rho \frac{\partial h_c}{\partial t} dx \cdot w_c = \rho w_c h_c dv(x,t) - \rho w_c h_c dv(x+dx,t) - J_s w_c dx$$

Rate of change of solute (kg/sec)

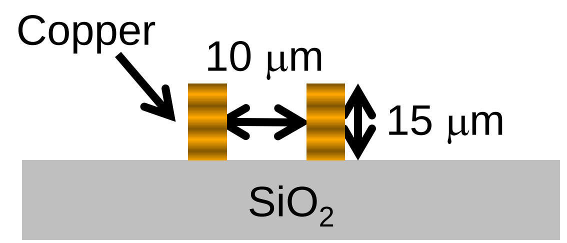
$$\frac{\partial}{\partial t}(c(x,t)) = -\frac{\partial}{\partial x}(c(x,t)\cdot v(x,t)) + D\frac{\partial^2}{\partial x^2}c(x,t)$$

Solve for nanoparticle concentration over time using FEA

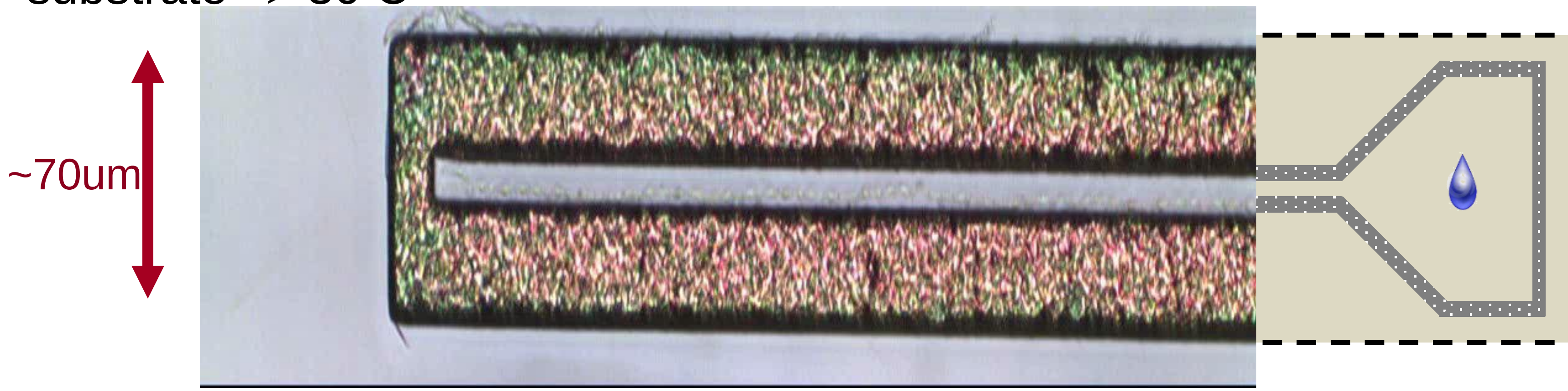


*Bedair et al., J. App. Physics 2009

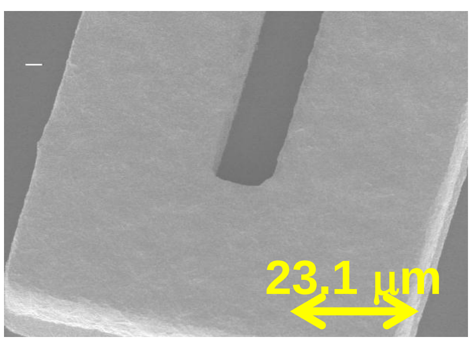
Filling Process



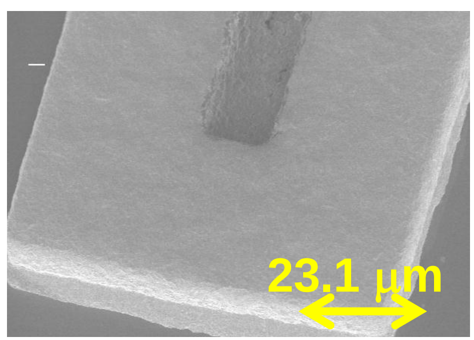
- 30 nm $NiFe_2O_4$ in methanol suspension
- 2 mm long, 10 μm wide, 15 μm tall channel
- Drop *by hand* ~ 1 μL from a 10 μL syringe, substrate –> 30 C



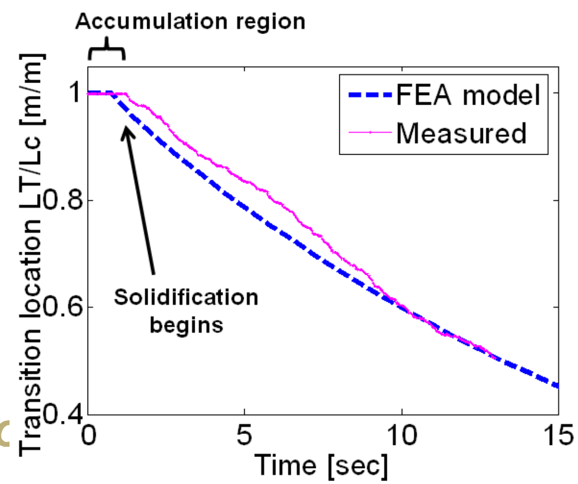
Before



After



Comparison w/ Theory

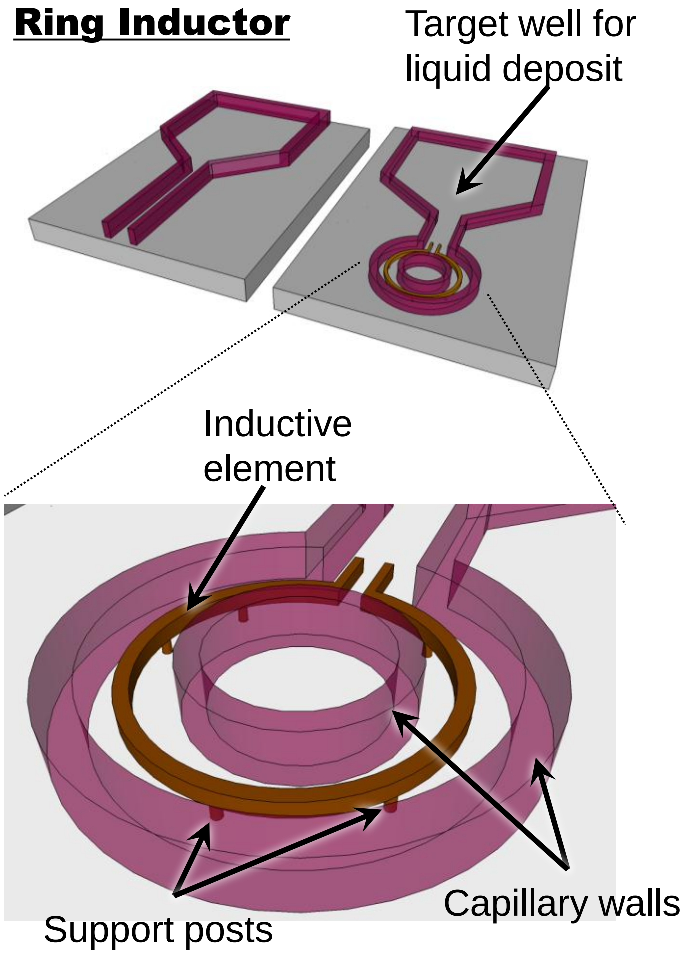


Bedair et al., TMAG 2010

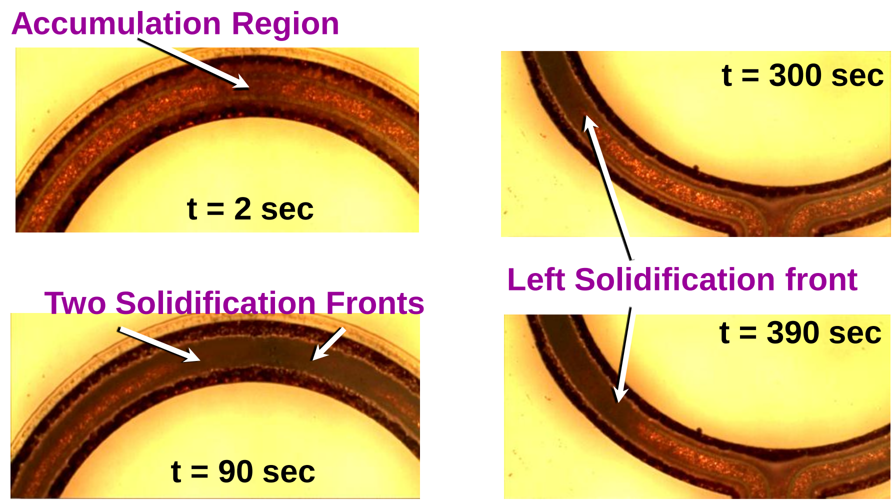
Closed Core Deposition

- **Trace suspended within circular channel.**
- **Magnetic NPs deposited fully around trace in single step.**

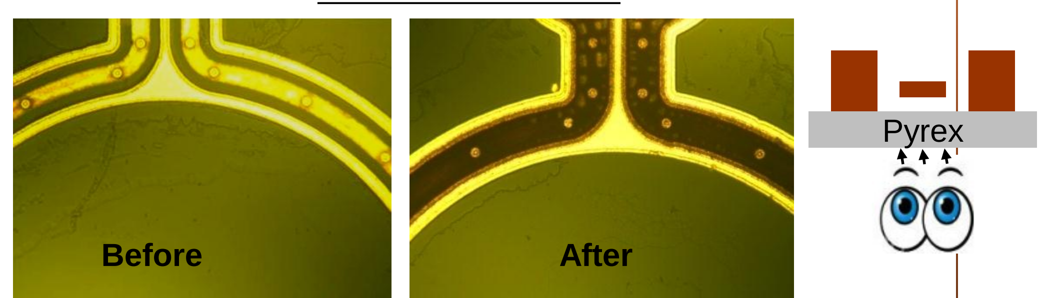
Ring Inductor



Top View During Deposition



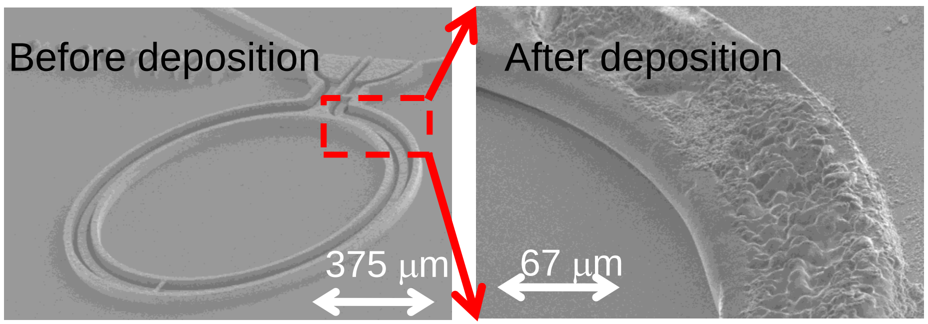
Backside View

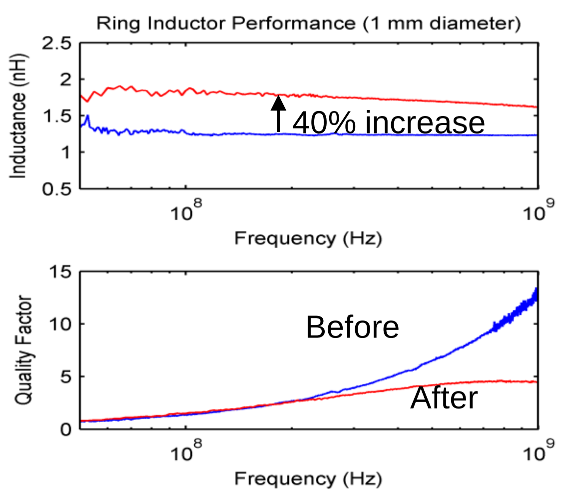


Demonstrated passives integration

Ring Inductor

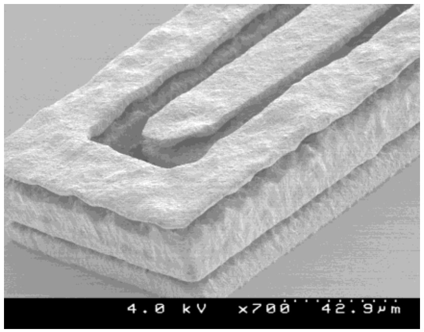
- Wicked ring inductors w/ Ni-ferrite nanoparticles (30 nm)

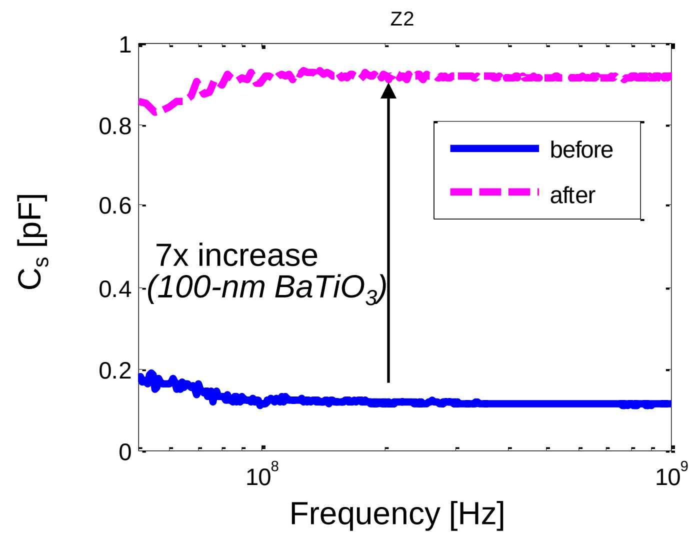




Parallel plate capacitors

-Dual channel parallel plate capacitor
- Measured capacitance before / after solution wicking & complete solvent evaporation





S. Bedair et al. *JAP* 2011

Piezo MEMS Transformers

Why piezoelectric transformers (PT)?

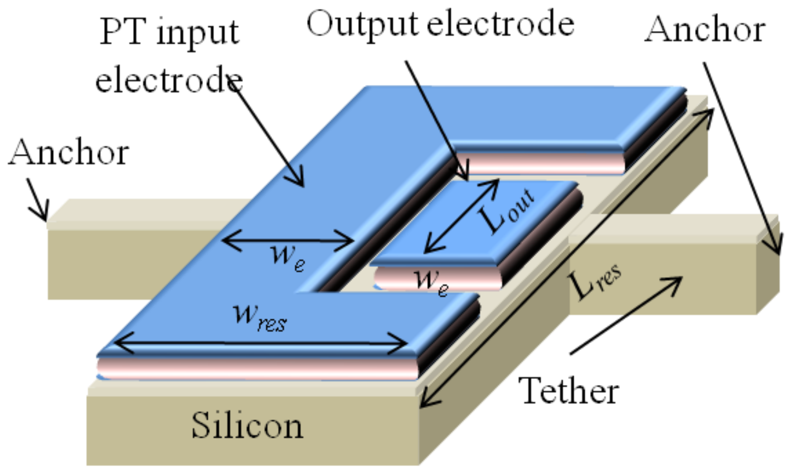
- Bulk PT's used for small size, high voltage isolation, low EM noise

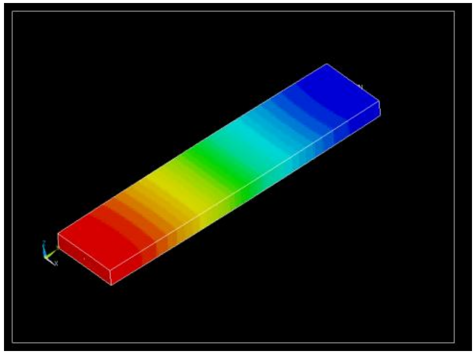
Challenges?

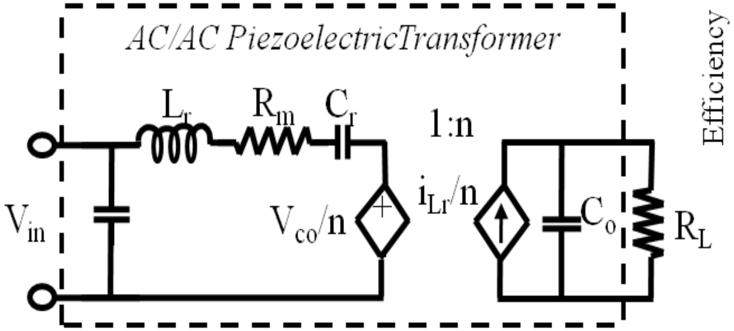
- AC/AC performance (efficiency, gain, power) depends heavily on R_L

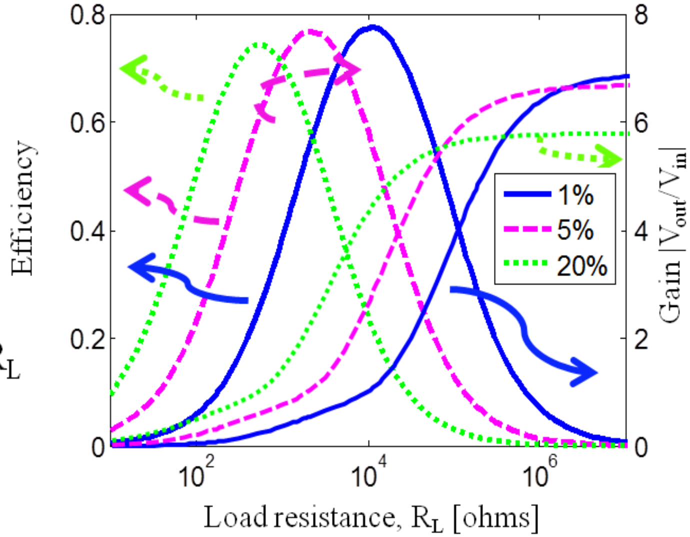
Current work:

- Leverage ARL expertise in thin-film PZT-MEMS
- Characterizing power handling & load dependence of gain and efficiency









Potentially 2-orders of magnitude smaller than traditional converters

*Bedair et al, Power MEMS 2009

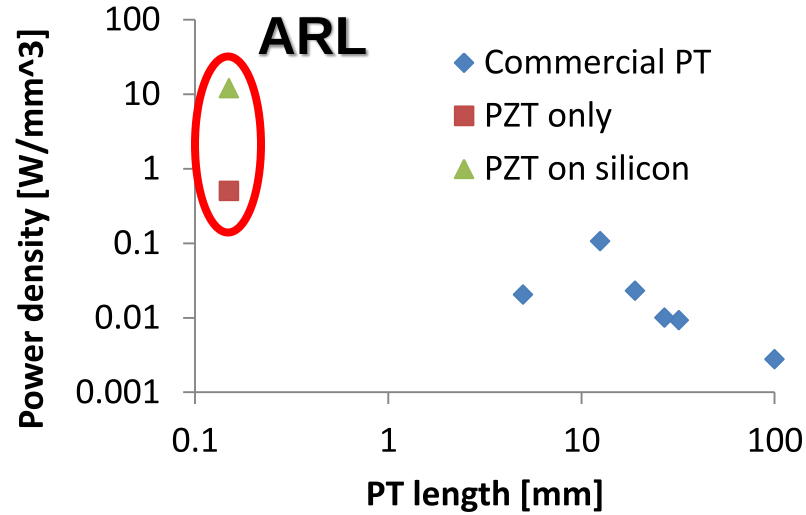
Piezo MEMS Transformers

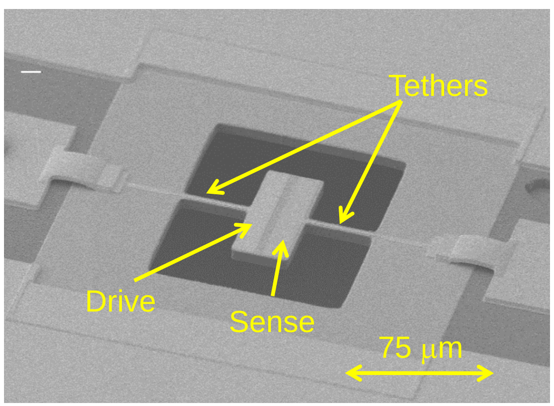
PZT on SiO_2 vs PZT on Si

- Stiffer support increases power handling
- Early results:
  - PZT on Si exhibits >20X power handling
  - AC voltage boost >2X demonstrated

Future work:

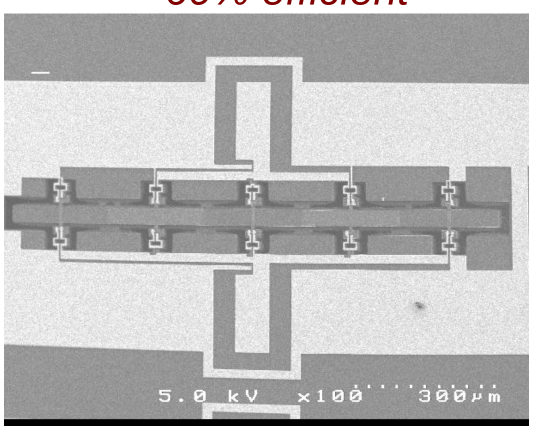
- Further characterize power, efficiency, gain characteristics for new designs
- Modify process for multi-layer PZT (voltage buck or boost)

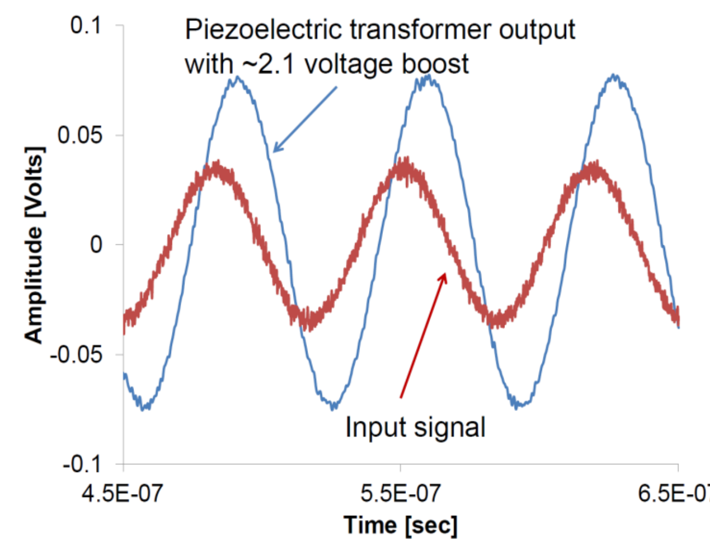




Gen 1 → fundamental mode, ~10% efficient

Gen 3 → 9th order mode, ~60% efficient



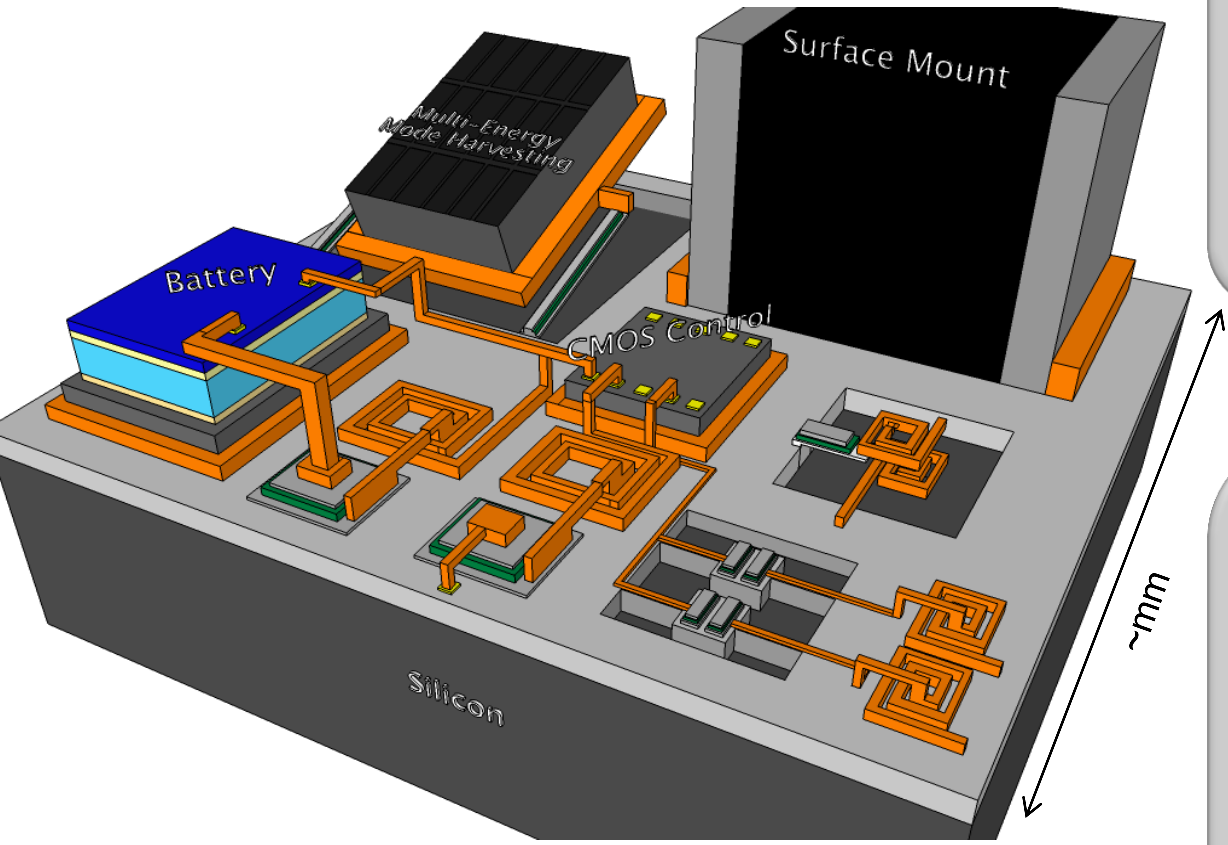


1st Demo of Voltage Gain (15MHz)

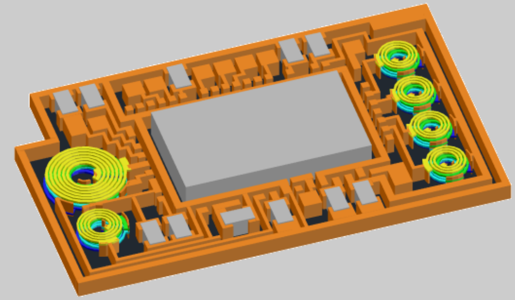
**Bedair et al, Power SoC 2010*
**Bedair et al., MEMS 2012*

The Future…

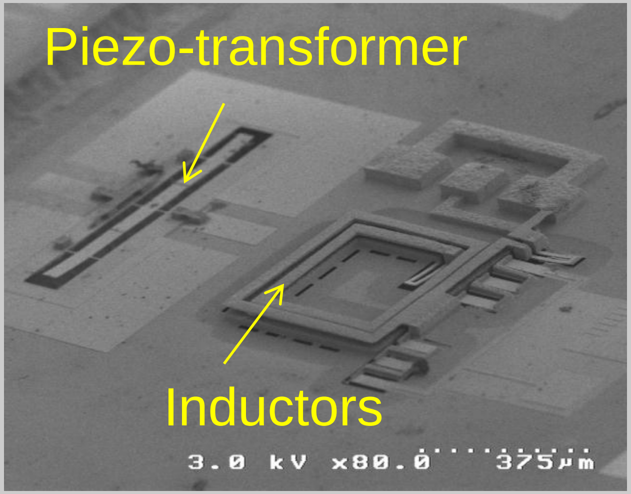
Single-chip power scavenging and control



Heterogeneous Integration

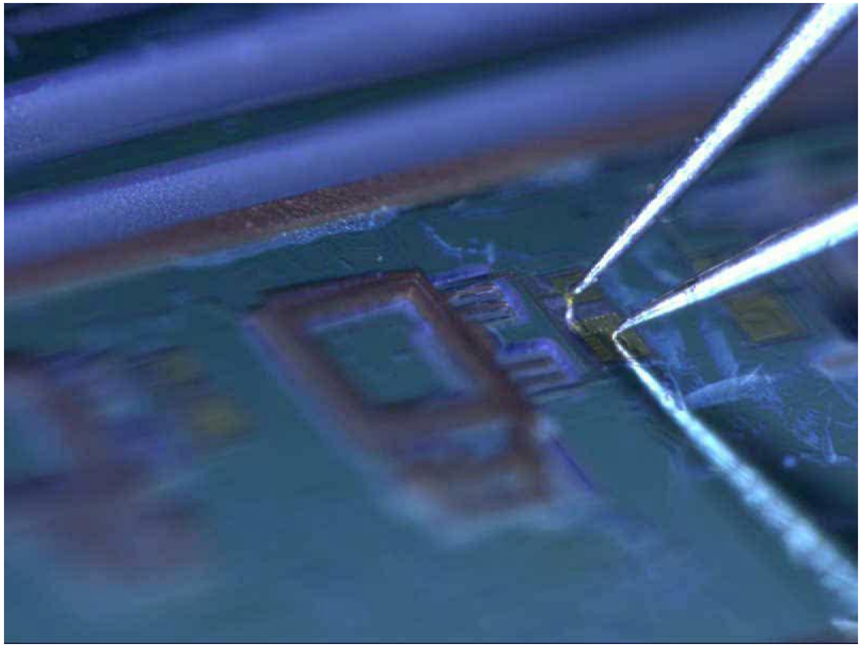


Monolithic Integration

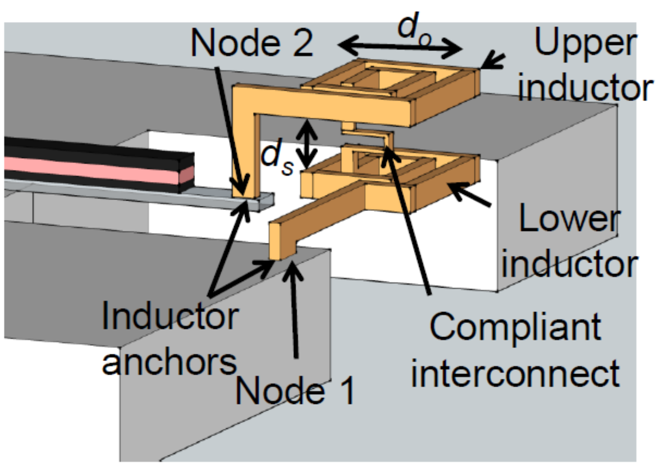


Tunable passives

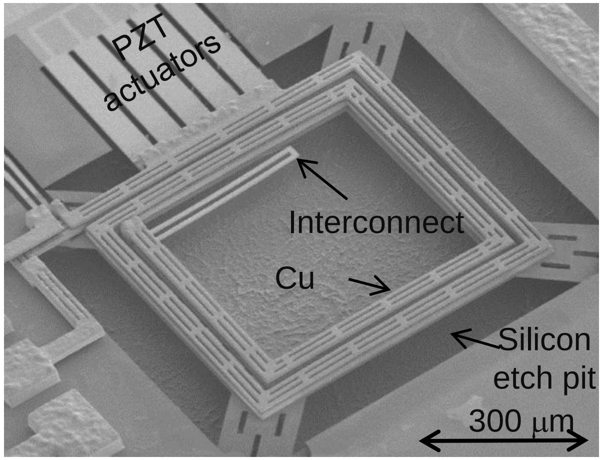
- **Combine inductor process with PZT MEMS actuator process to create tunable passive components**
  - Control for power electronics
  - Tunable RF components
- **Demonstrated high performance, tunable inductors**
  - Tuning ratio ~2.7:1
  - Q's > 10



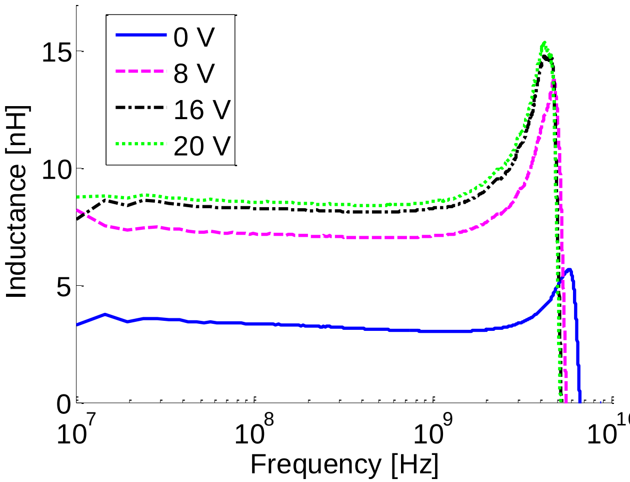
Device concept



Fabricated device



Measurements

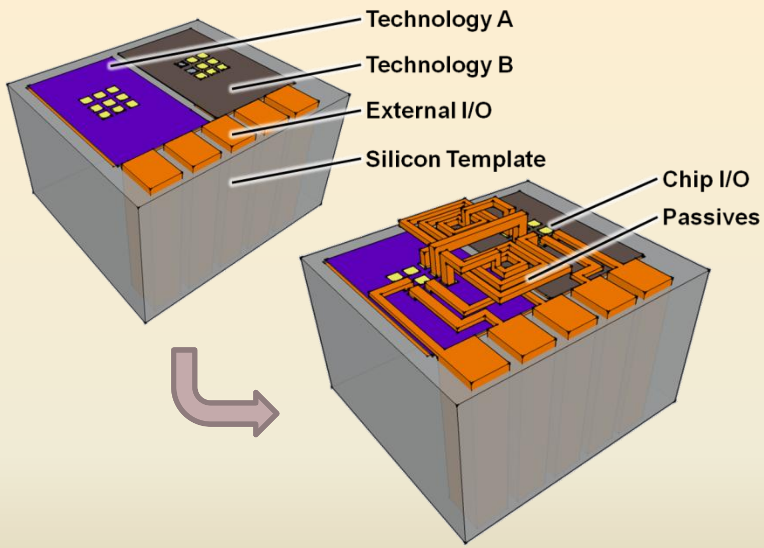


* S. Bedair et al. *EDL 2012* (accepted).

Heterogeneous Integration: How To Get There

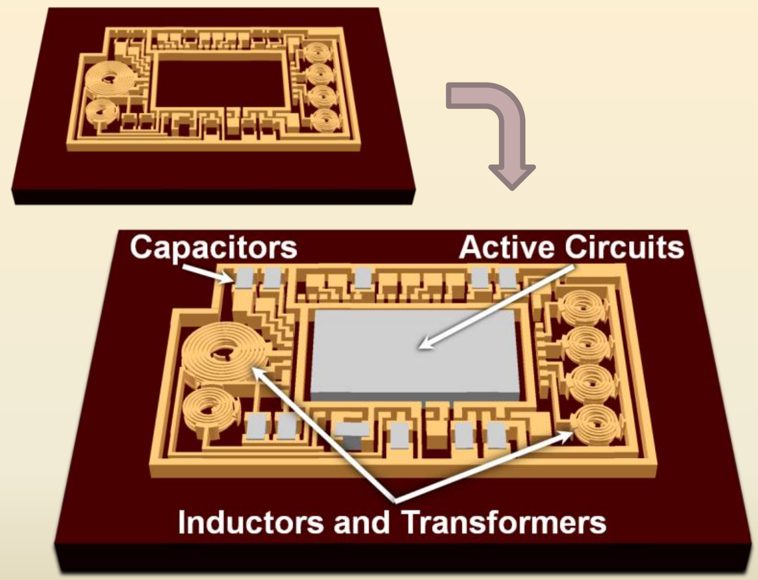
Heterogeneous Integration Strategies

Chip-First



- Embed chips w/in **template wafer**
- Fabricate passives and **routing last**.

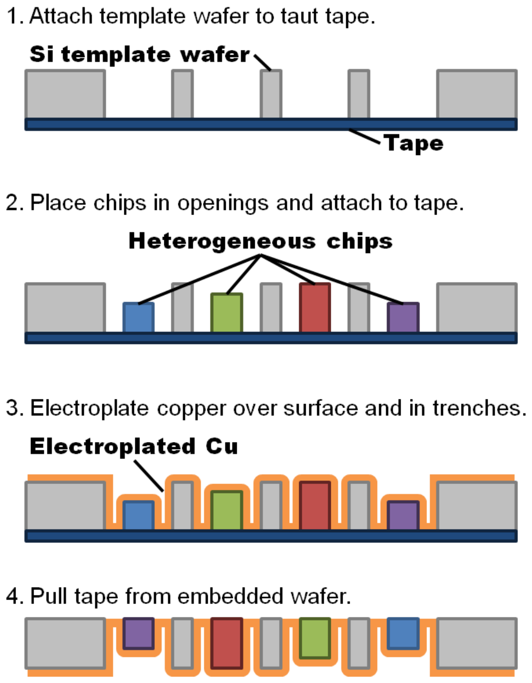
Chip-Last



- Fabricate passives and **routing first**.
- Embed chips w/in **3D copper scaffolding**.

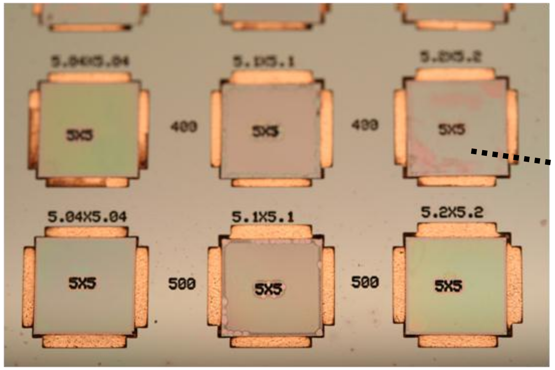
Chip-First Integration

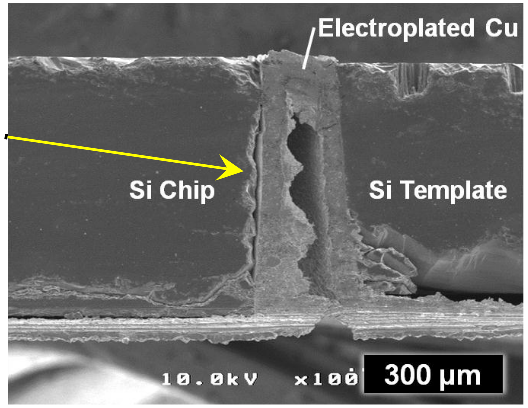
- **Microfabricated silicon template by DRIE.**
- **Template and chips mounted co-planar.**
  - Measured planarity w/in ~5 µm
- **Aligned chips using template corners.**
  - Maximum lateral offset < 40 µm.
- **Electroplated 60 µm thick copper to embed.**
- **Planar surface to be post-processed to form passives and interconnects.**



Silicon template

Embedded chips

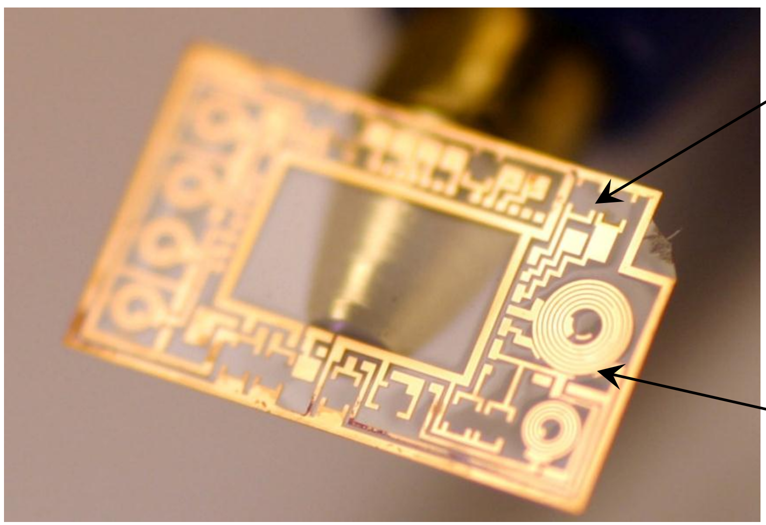


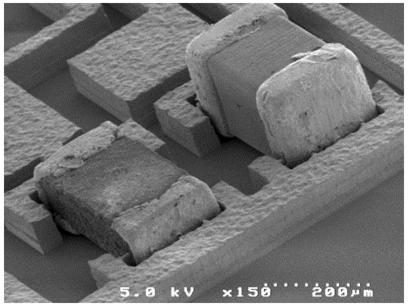


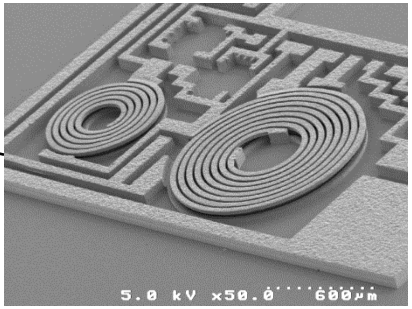
*C. Meyer, et al. *ECS 2012.*

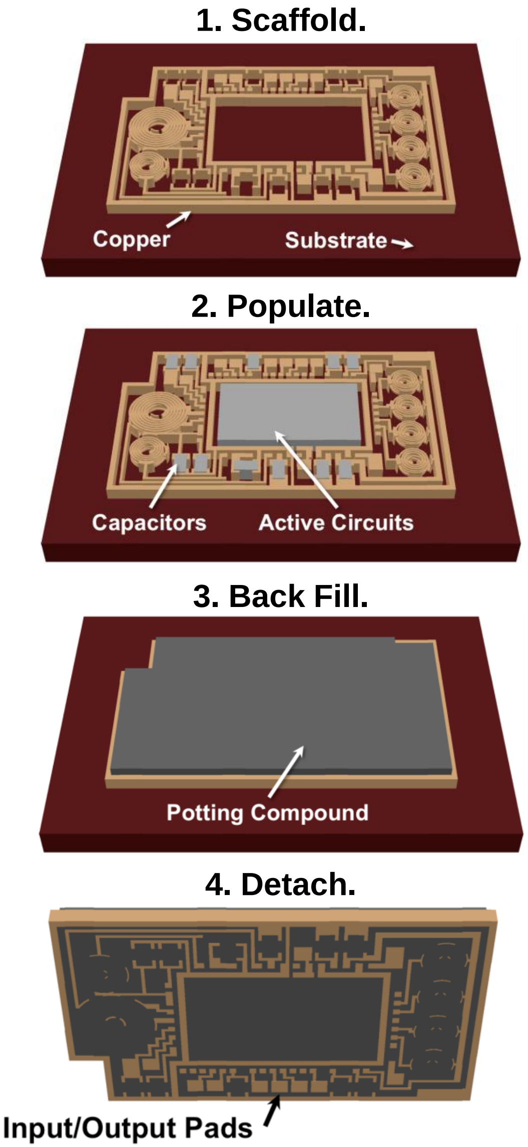
Chip-Last Integration

- **Scaffolding fabricated by 3D copper process.**
  - Total thickness 90 µm.
  - High aspect ratio >10:1 for dense routing and passives.
- **Deformable sockets for press-fit integration.**
  - Alignment & prevents tombstoning of parts.
- **Will be demonstrated w/ 3-in-1 VHF CMOS converter die.**





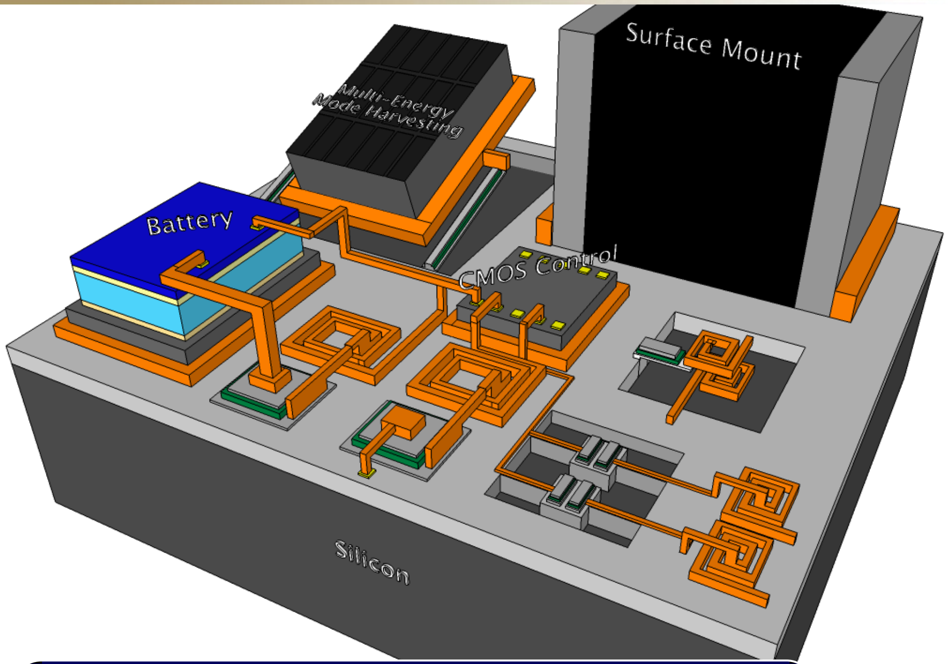




*C. Meyer, et al. *Hilton Head 2012.*

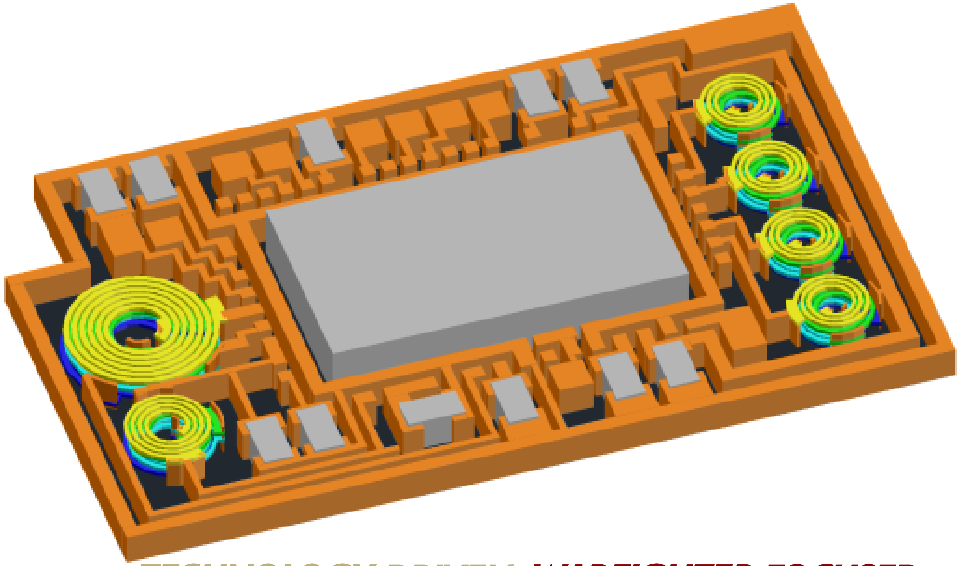
Questions?

The Future...

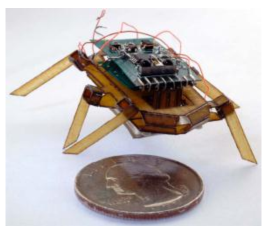
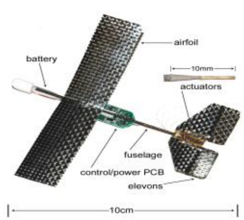
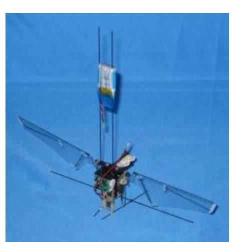


Single-chip multi-modal power scavenging and control

Inductors holding chips instead of chips holding inductors



Mass Distribution for Micro-Robot

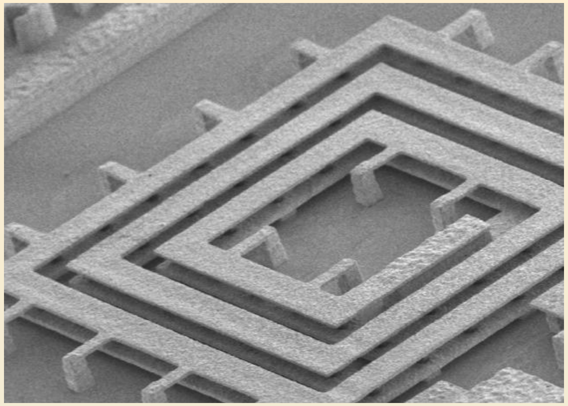
System		Total Mass	Battery	Other Power Components (motors, controllers, etc)
Harvard Micro Fly (projected)		0.12g	42%	38%
Berkeley RoACH		3g	23%	24%
Berkeley Glider		2g	32%	19%
Daedelus Flapper		11.8g	22%	27%

*Morgan et al., SPIE 2010

Complementary Paths

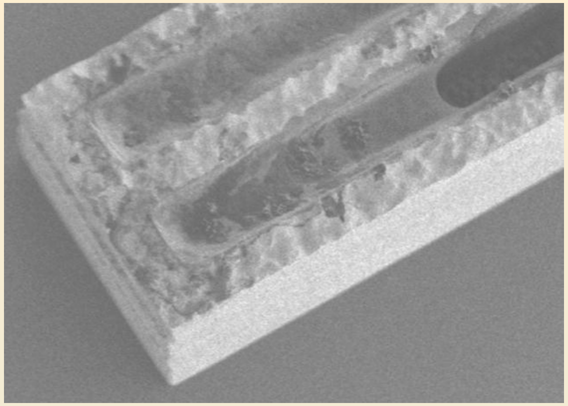
3D Copper Micromachining

Air-Core Magnetics



- Optimize coil for 50-500 **MHz switching**.
- Vertical **stacking**.
- **Thick copper** traces.
- **Air gaps** around traces.
- Inductance densities **> 100 nH/mm^2**.
- Quality factors > 20.

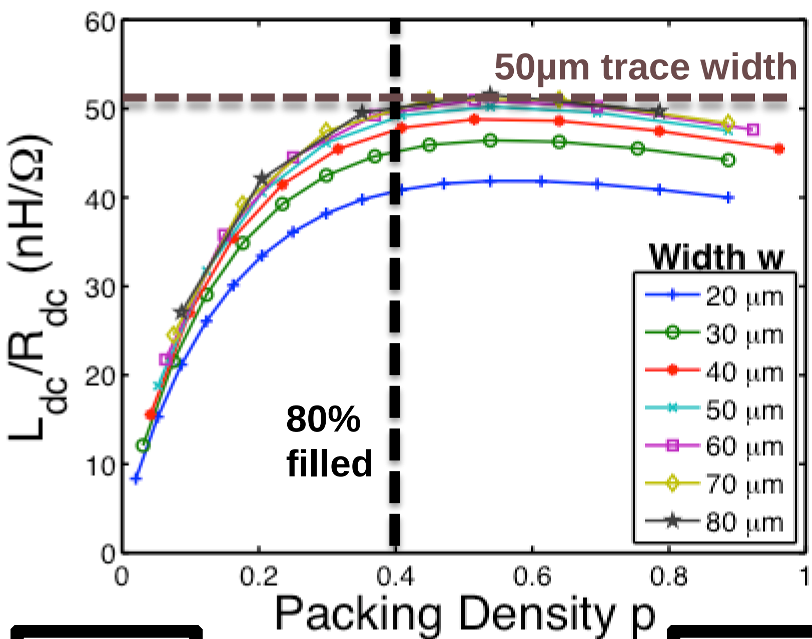
Capillaries for Nanoparticle Deposition



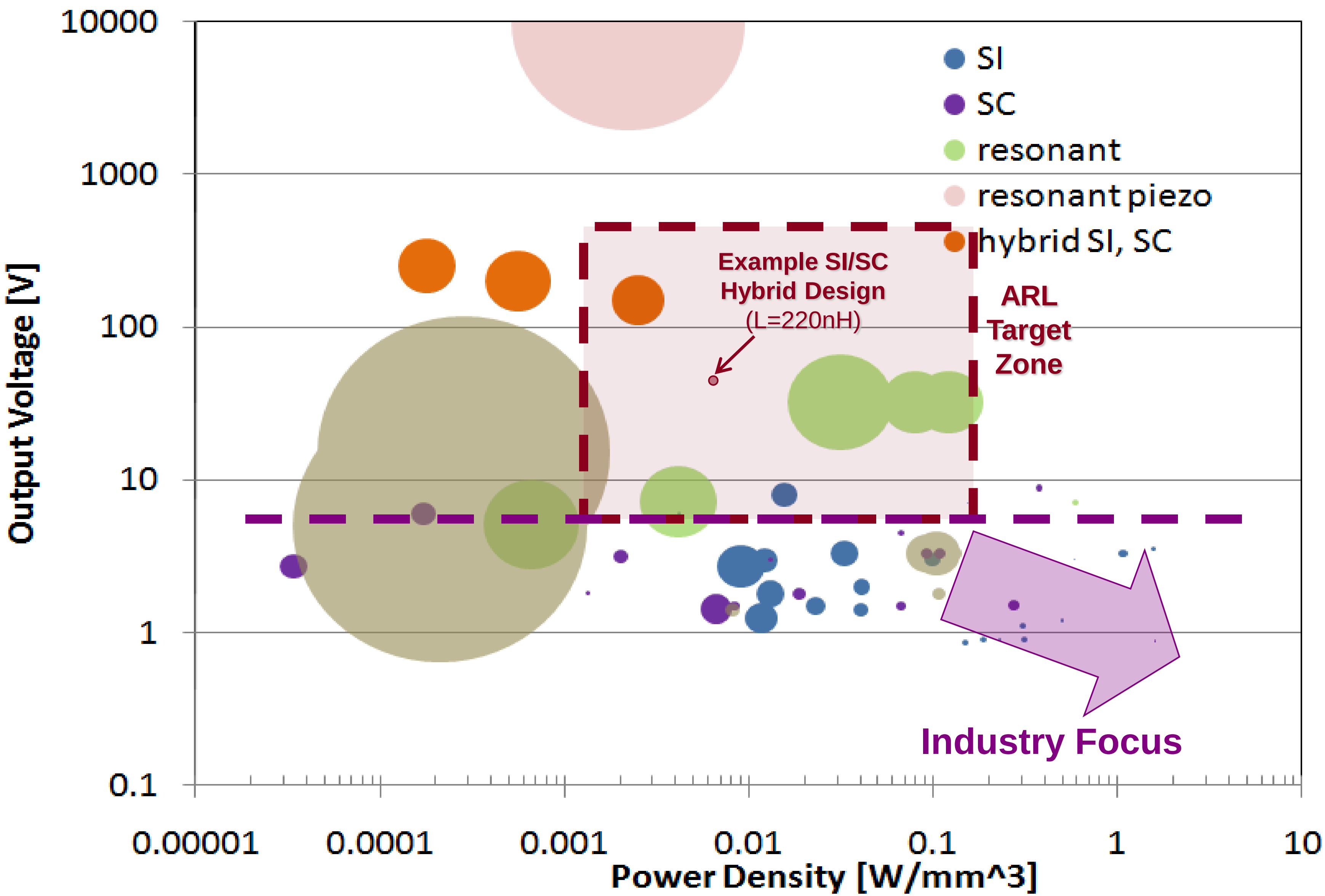
- Nanoparticles with **low loss at MHz.**
- **Fluidic, capillary-driven** packing into mold.
- **Single-step** deposition and patterning.
- Full **encapsulation** of floating structures.
- All **room temperature** process.
- Compatible w/ **any nanoparticle** material.

Air Core Inductor Design

- Analytical expressions to determine geometry.
  – Mohan, et al, “Simple accurate expressions for planar spiral inductances,” *IEEE JSSC*, 1999.
- Stacking for increased density.



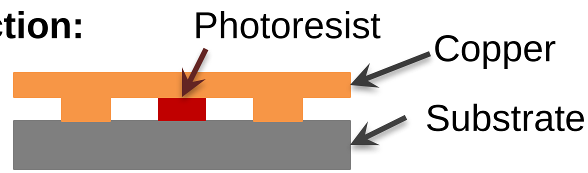
Power Converter Research: Where do we fit?



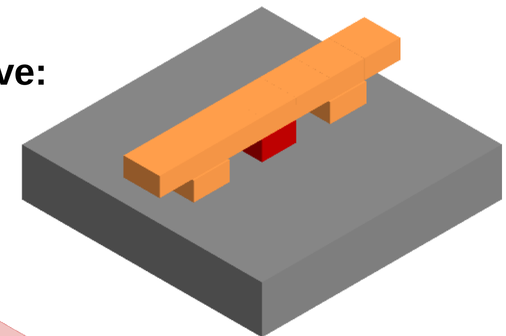
Microfabrication Example

- **Example: Form a copper beam with photoresist support post.**

Cross section:

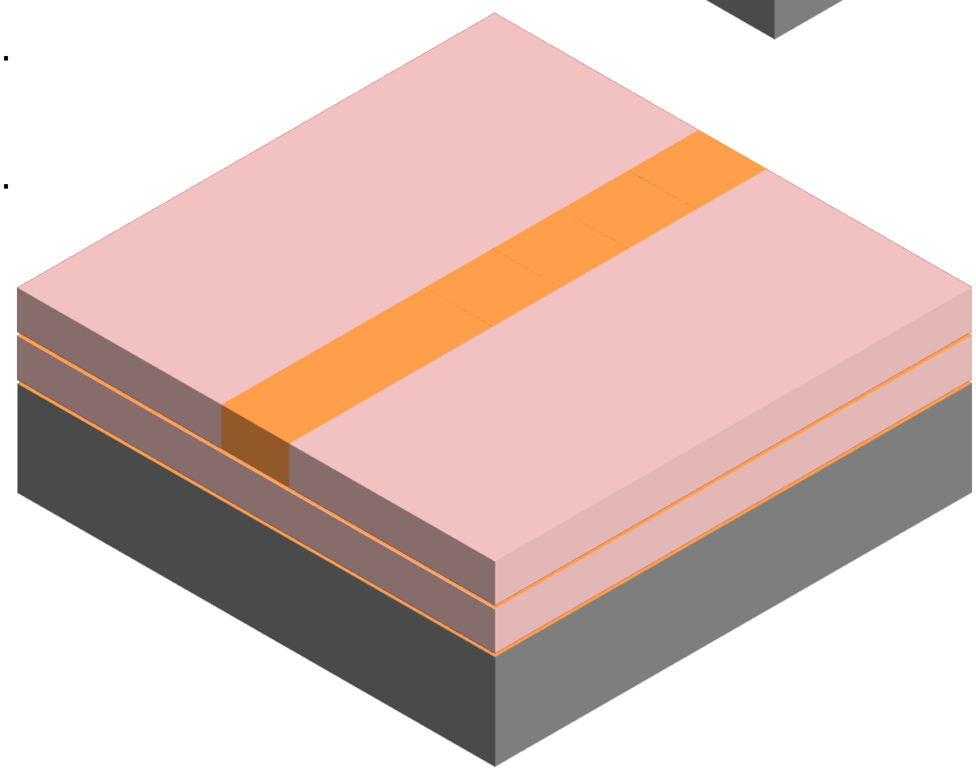


Perspective:



Sputter Cu seed.
Spin photoresist.
Expose.
Develop.
Expose.
Electroplate.
Sputter Cu seed.
Spin photoresist.
Expose.
Develop.
Expose.
Electroplate.

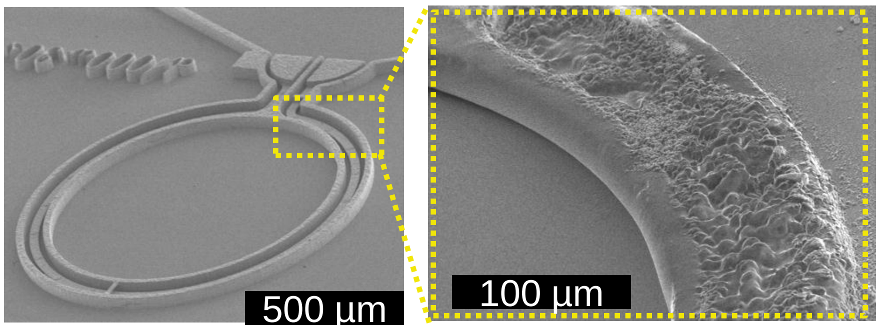
Develop.
Etch seed.
Develop.
Etch seed.

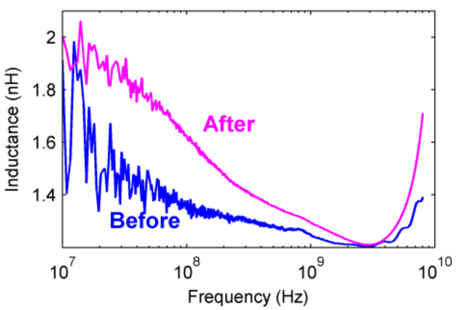


Passives Co-Integration

Ring Inductor

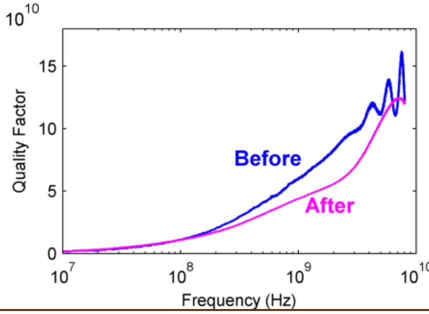
- **30 nm $NiFe_2O_4$** ferrite mixed into IPA, *n*-butanol, diacetone alcohol and B-79 PVB.





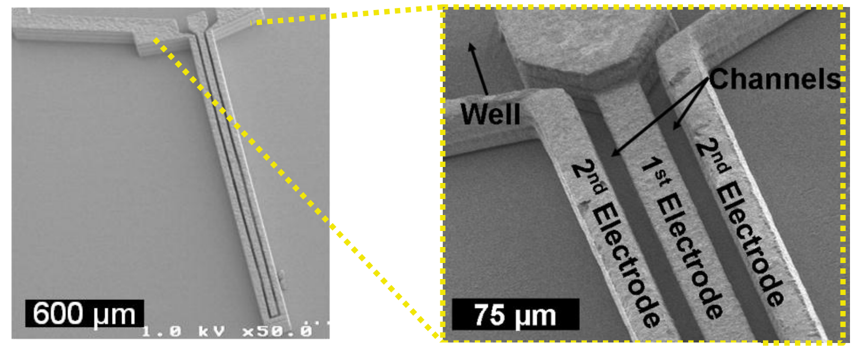
- ~25% inductance boost.

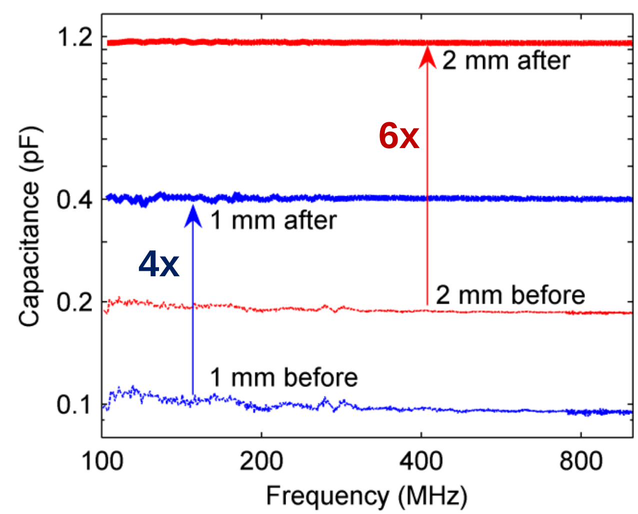
- No detriment to Q up to 100 MHz.



Dual-Channel Parallel Plate Capacitors

- **100 nm $BaTiO_3$** dielectric mixed into IPA, *n*-butanol, diacetone alcohol and B-79 PVB.

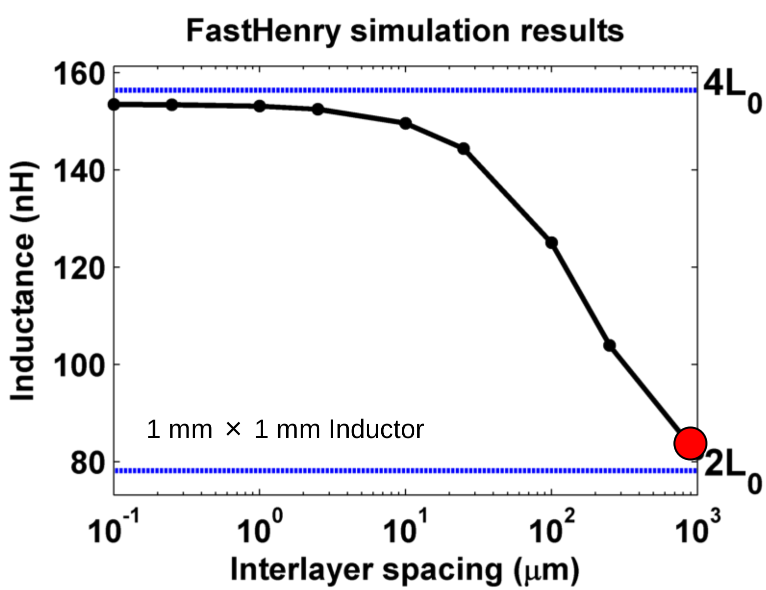


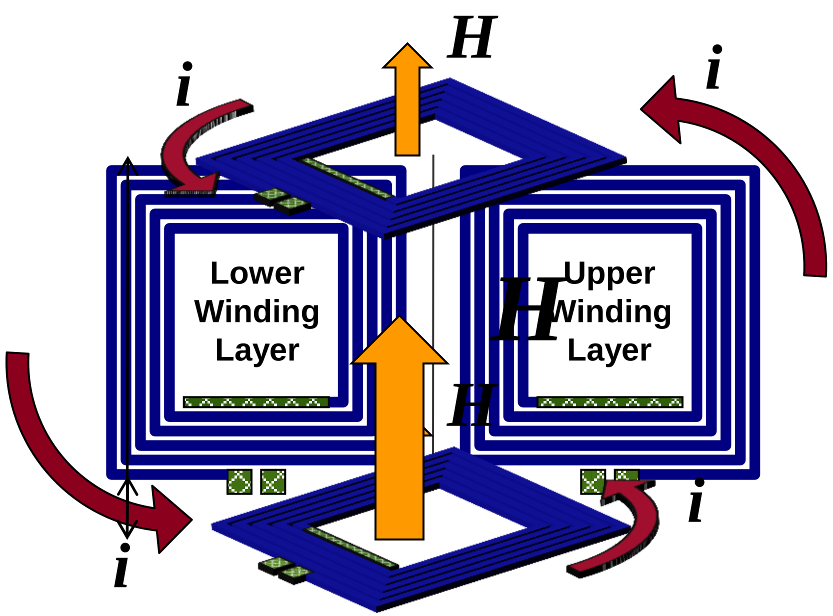


*Bedair et al., J. App. Physics 2011

Approach for high Q (>20):

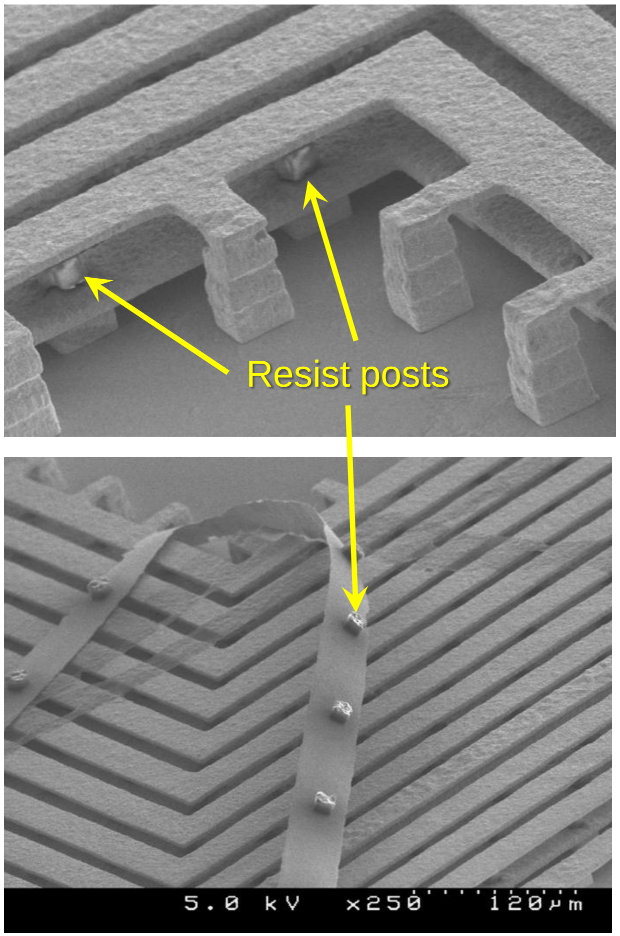
1. **Air-core stacked spirals**
   - Eliminates high frequency magnetic losses & magnetic fabrication complexity
   - Stacked windings for 4X inductance over single layer [1]
2. **Thick Cu traces for low resistance**
3. **Patterned inter-layer dielectric for low capacitance**



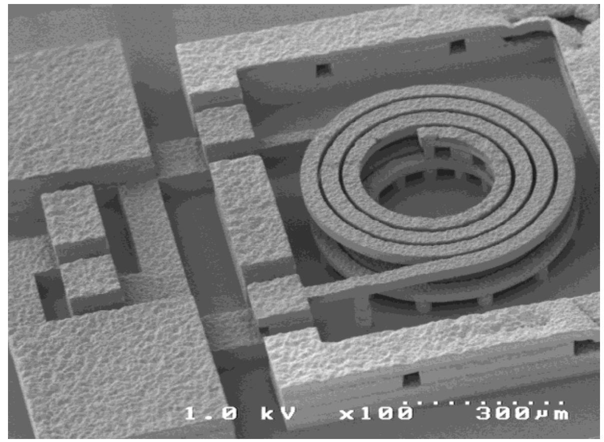


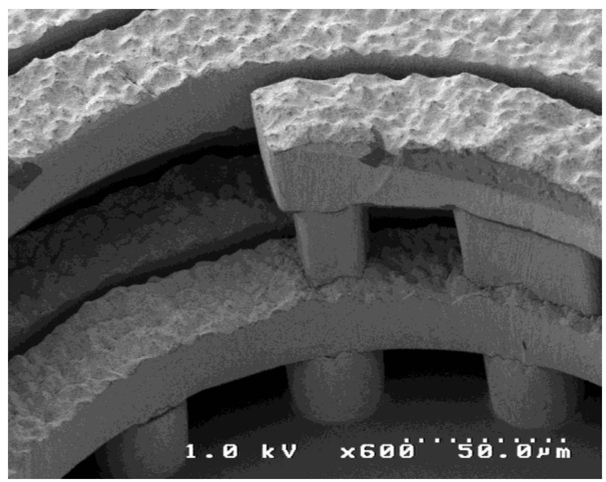
[1] Geen, et al., "Miniature Multilayer Spiral Inductors for GaAs MMICs," *GaAs IC*, 1989.

3D Electroplated Copper

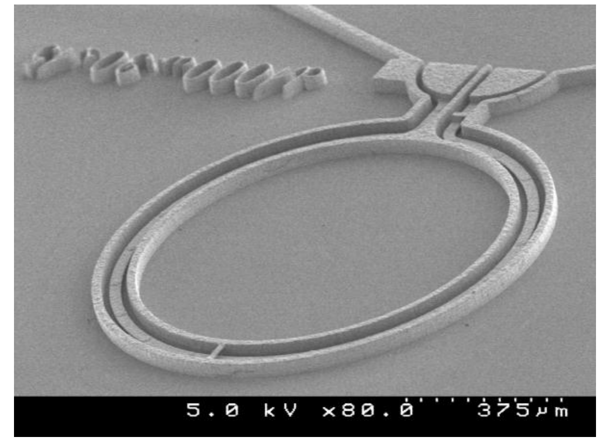


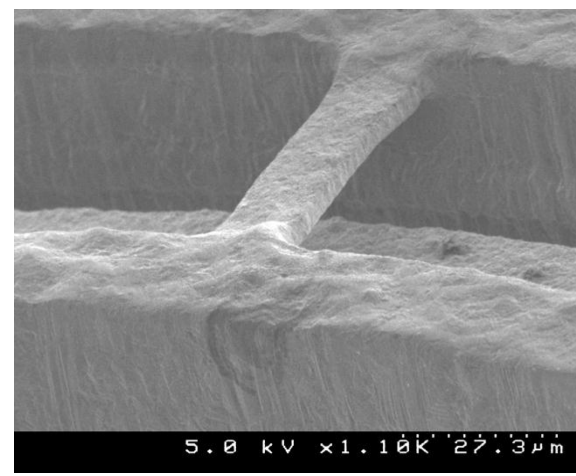
10um Cu,
Resist posts





30um Cu,
no posts





10um Cu,
microfluidic channels

Piezoelectric Materials
Why Ferroelectrics?

Advantages

- High piezoelectric coefficients
- Piezoelectricity scales well with thinner films
- High electromechanical coupling coefficients

Disadvantages

- New materials set for many clean rooms (both piezoelectric and electrode)
- Few foundries for ferroelectric films
- Comparatively high processing temperatures

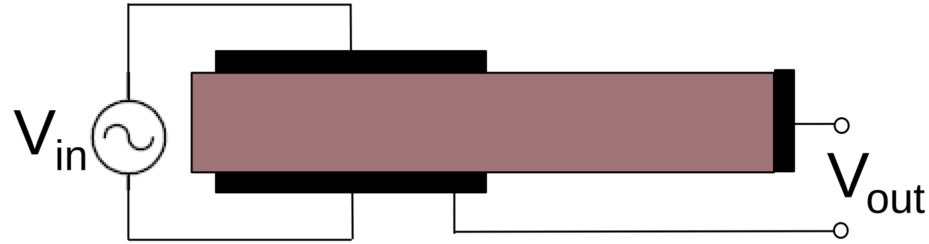
	ZnO	AlN	PZT 52/48
$\varepsilon_{33,\,f}$	8 - 12	10.4	900 - 1300
$d_{33,\,f}$ (pC/N)	10 - 12	3.4 - 3.9	90- 110
$e_{31,\,f}$ (C/m^2)	-0.43 to -0.8	-0.9 to -1.0	-10 to -18
$k^2_{p,f}$	0.06 - 0.085	0.065 - 0.11	0.1-0.20

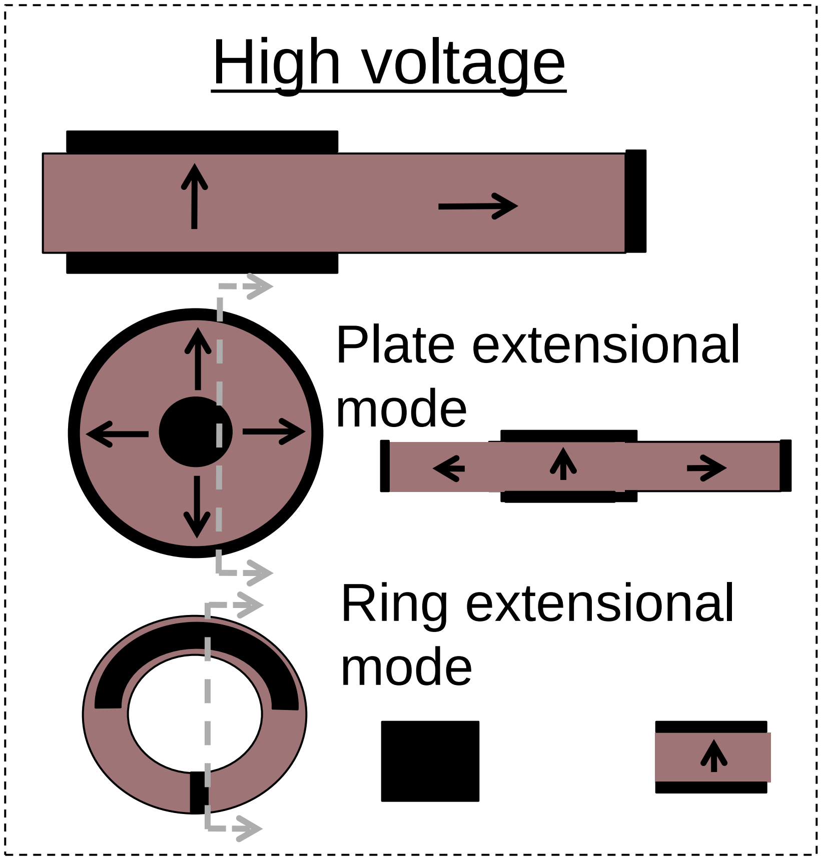
P. Muralt, IEEE Trans. UFFC 903 (2000)

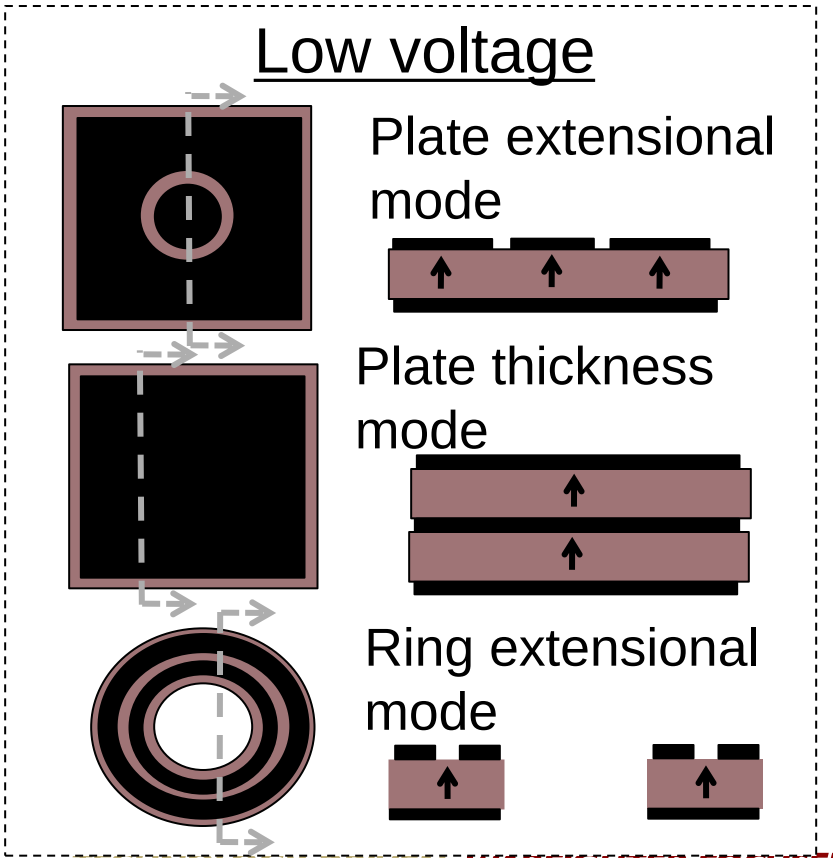
$$k^2 = \frac{\textit{Mechanical Stored Energy}}{\textit{Electrical Input Energy}}$$

Modes of operation

- Wide variety of modes
- Rosen, traditional type, but difficult to realize using traditional fabrication

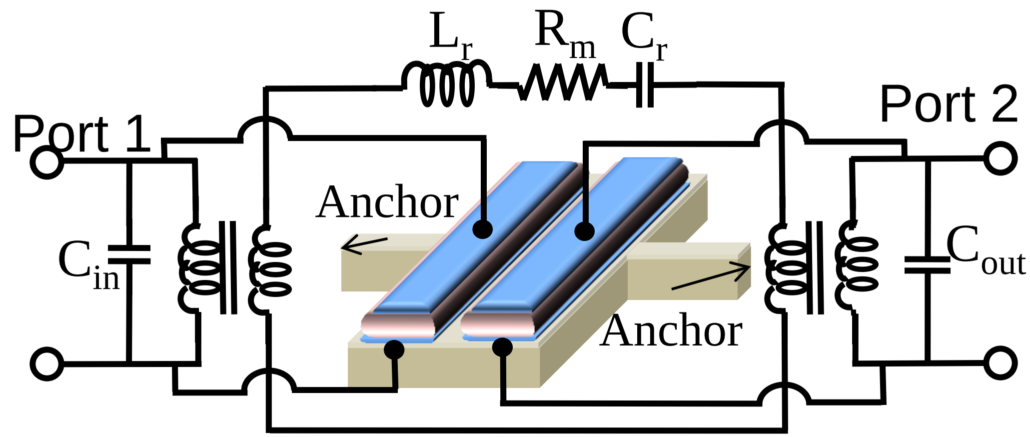






J. Yang, *IEEE TUFFC*, 2007.

Equivalent circuit model



Modal force

$$F_1 \propto e_{31} V_1 A_{in}$$

Charge on output

$$Q_2 \propto e_{31} \bar{Z} A_{out}$$

Electromechanical coupling coefficient – input & output

$$\eta_{in} \propto e_{31} A_{in}$$

$$\eta_{out} \propto e_{31} A_{out}$$

R, L, C equivalence

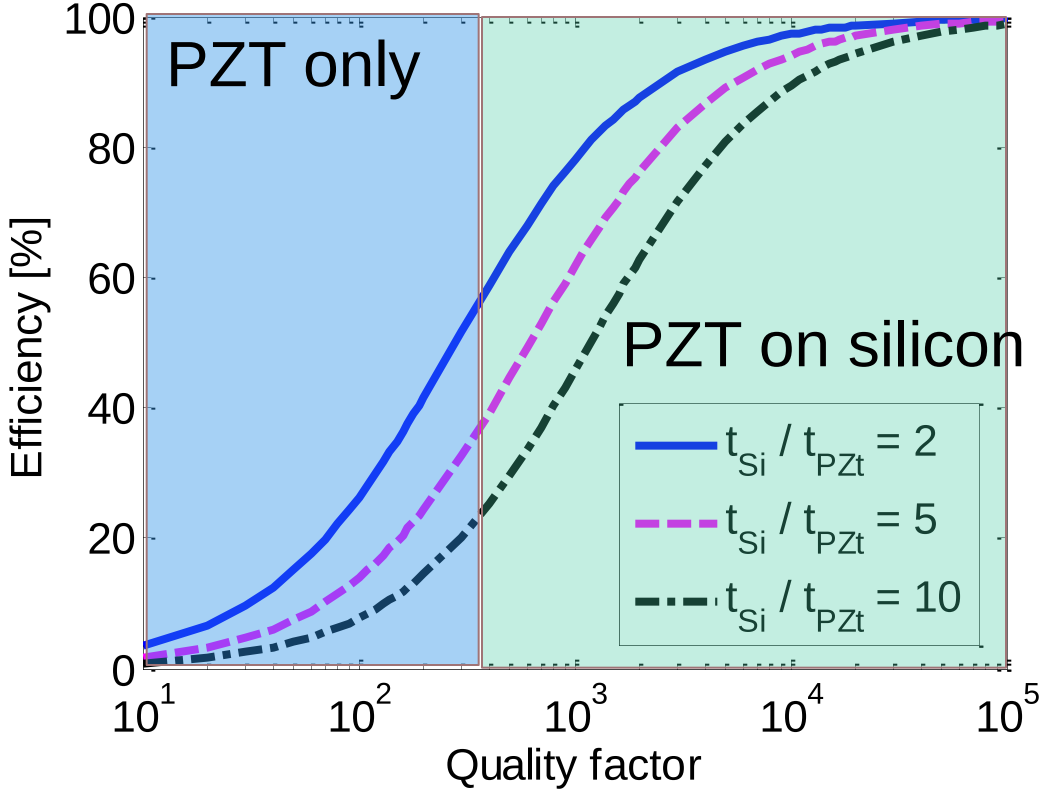
$$L_r = \frac{mass}{\eta_{in}\eta_{out}} \quad C_r = \frac{\eta_{in}\eta_{out}}{k_n}$$

$$R_m = \frac{n\pi A_x \sqrt{E_i \rho_m}}{2Q} \frac{1}{\eta_{in}\eta_{out}}$$

Peak Efficiency

- Efficiency versus Q factor, k_{31}= 0.3
- PZT only Q < 400
- With silicon, trade Q for effective electromechanical coupling factor

$$\eta = \frac{R_o''}{R_o''+R_m} = \frac{1}{1+\frac{n^2\pi^2}{2Q}\frac{1}{k^2{}_{31}}\left(1+\frac{t_{Si}}{t_{PZT}}\frac{E_{Si}}{E_{PZT}}\right)}$$

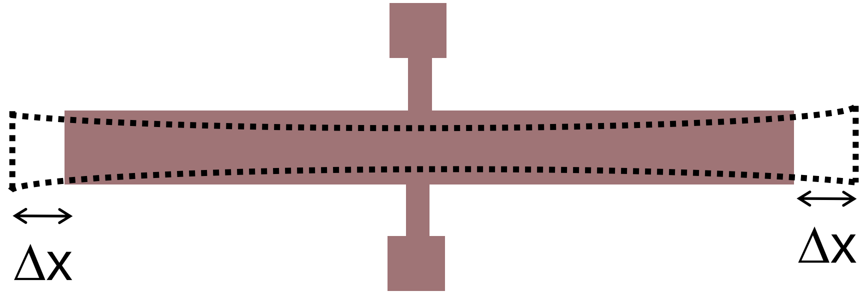


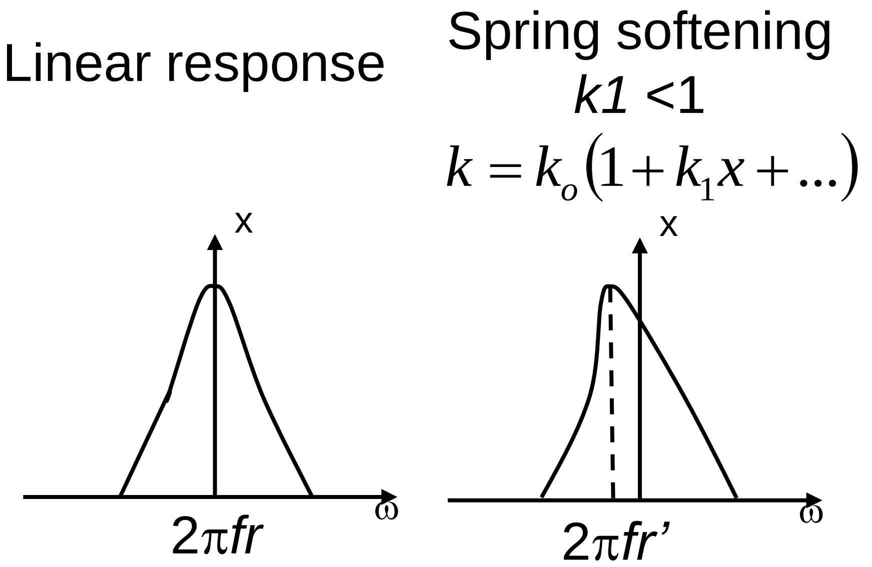
Power handling

- Critical vibration amplitude, x_{cr}, from a critical strain, ε_{cr}
- Mechanical energy stored per cycle

$$E_m = \frac{1}{2} k_o x_{cr}^{\ 2} \propto E_c A_c x_{cr}^{\ 2}$$

- With silicon, composite elastic constant, $E_c >> E_{pzt}$
- Power ~ $E_m * f_r$
- Fundamental tradeoff of efficiency & voltage gain vs. power handling vs. *Q*
- Lower thermal resistance to thermal ground
- Non-linearities manifest as spring softening or spring stiffening terms in the frequency response





V. Kaajari, et al., *JMEMS* 2008.
A. Flynn & S. Sanders, *IEEE Trans. Pow. Elect.* 2002.